Atomic Artillery

ATOMIC ARTILLERY
Modern Alchemy for Everyman

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PREFACE

In this little book an attempt has been made to explain in language intelligible to a layman the story of fascinating developments in one branch of modern physics. At a time when the daily press treats as "news" the latest discoveries in science and gives a prominent place in press dispatches to the proceedings of the British and the American Associations for the Advancement of Science, it is felt that a scientist need offer no apology for writing a book for the benefit of the non-specialist.

With the exception of a very little addition and subtraction, the book is absolutely non-mathematical and demands nothing but an intelligent interest on the part of the reader. Assuming no technical knowledge, it tells the story of electrons, protons, positrons, photons, neutrons, and cosmic rays, and it explains step by step the games of shooting atoms, of turning one element into another, and of manufacturing a radioactive material from common salt.

In addition to the general reader, it is hoped that ATOMIC ARTILLERY will be of value to the young student beginning the study of either physics or chemistry, and to all students, both young and old, who seek a general acquaintance with some of the revolutionary discoveries in modern physics. To radiologists who daily shoot radium rays and x-rays and to all those interested in biological applications of neutron bombardment and of artificial radioactive elements, the book is also commended.

In the preparation of the book, the author has been assisted greatly by all those whose kindness has enabled him to reproduce the photographic illustrations. His grateful thanks are due Prof. E. O. Lawrence for photographs of the cyclotron; to Dr. Kenneth T. Bainbridge for photographs of mass spectra; to Dr. Seth H. Neddermeyer and Prof. Carl Anderson for cosmic ray expansion chamber photographs; and to Sir J. J. Thomson, Dr. F. W. Aston, Prof. C. T. R. Wilson, Prof. P. M. S. Blackett, Prof. E. T. S. Walton, Dr. P. I. Dee, Dr. N. Feather, Julius Springer, Longmans, Green and Company, the Royal Society, the Physical Review, and the Journal of the Franklin Institute for permission to reproduce illustrations previously published.

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INTRODUCTION

From early childhood we have all been familiar with certain aspects of the world around us. No sooner do we learn to walk than we find that our ability to move about is subject to restrictions. If we are not careful we bump into a table or a chair, or perchance we lose our balance and find our fall suddenly stopped by the hard floor beneath us. As we grow older it is much the same story. Whether we walk or run or ride in a car, we must constantly change our direction to avoid colliding with something, or somebody. Our freedom to move about in what we ordinarily call space is restricted by the presence of what we call matter.

But it would not do to define matter as that which restricts our motion, because if it were not for matter we could not move at all. Trains are matter and the rails on which they travel; so too are ships and the water through which they plough; airplanes and airships are matter and the air which they sweep aside; and when we ourselves walk, we must

have something material to walk on. The food we eat is matter, and if we stop eating for long, soon we become unable to move any part of our bodies, which are matter too. Indeed it is impossible to think of terrestrial life apart from matter. It is true that we are familiar with such non-material things as radio and light waves, but neither of these entities can be produced or detected without matter. Electricity, too, is an intangible thing, but all its manifestations are through matter.

The fact is, we cannot get away from matter, and the nature of its ultimate structure underlies most of the questions with which physics or any branch of natural science has to deal. The geologist with his rocks and fossils, the chemist with his compounds, the botanist with his plants, the biologist with his animals, the bacteriologist with his microbes—all are studying some aspect of matter. The philosopher may question the existence of matter apart from mind, but the scientist accepts without question the objective reality of the external world about him. For the scientist, matter is anything which reveals its presence, directly or indirectly, by sense-impressions, and upon which he can make observations and measurements.

It is not surprising, therefore, that from times

which almost antedate history, attempts have been made to interpret in terms of a few common constituents all the various forms of matter. In the discussions and speculations of the early Greek scholars we find examples of this. Philolaus, the Pythagorean, ascribed a definite geometrical form to the elementary particles of the primary substances, earth, air, fire, and water, and it has become a commonplace to refer to the atoms of Leucippus and his more famous pupil Democritus.

The modern physicist, by experiment and measurement, has amply confirmed the ancient conception that matter is granular in structure. For a while the ultimate particles or the building bricks, were some eighty or ninety different kinds of atoms, but towards the end of the nineteenth century, the discovery of sub-atomic electrons showed that there was a common constituent,—a primordial substance, as it were, —in all atoms, and introduced a revolutionary change in the scientists' conception of matter. Investigations in radioactivity, a discovery of the same period, gave further evidence of the complexity of the atom, and indeed, showed that one atom could be changed into another. Throughout the twentieth century, the fascinating problem of unravelling the process of atom-building has been continued, the discovery of other

fundamental particles such as the positron and the neutron only serving to increase the interest in this pursuit. At the present time many investigations make use of a form of artillery in which the ammunition consists of pellets so small that it would take a few thousand million million million million of them to make an ounce, but moving so fast that, if given a chance, they would encircle the earth in less than a second. These investigations are rewarding the scientist with a wealth of new information about the structure of matter, and giving results of absorbing interest even to a layman. In this book it is our aim to tell, in simple and non-technical language, the story of atomic artillery.

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CHAPTER I

GRANULAR MATTER

Elements and Compounds

All the substances which occur on the face of the earth can be divided into two groups. In one we place those which can be decomposed chemically into two or more simpler substances, or can be manufactured by the union of simpler substances. These are called *compounds.* In the other we place *elements,* substances for which no such decomposition or synthesis is possible. Water is a compound, because, by passing an electric current through it, we can readily decompose it into two gases, oxygen and hydrogen; or, conversely, by suitably exploding a mixture of these two gases, water is the resulting product. On the other hand, neither oxygen nor hydrogen can be decomposed into simpler substances, and each is an element.

Sugar is a compound, containing the three elements carbon, oxygen, and hydrogen. The soda bicarbonate we buy in a drug-shop—another name for ordinary baking soda—is a compound containing four ele-

ments, sodium (a soft metal), hydrogen, oxygen, and carbon. If a green gas called chlorine is passed over the silvery metal sodium, the two unite vigorously to form the familiar white compound, common salt. But substances like silver, copper, gold, iron, iodine cannot be decomposed into simpler substances and are all elements.

The study of the analysis and the synthesis of compounds and their reactions with one another is one of the jobs of the scientific chemist. With the aid of the physicist, he has identified ninety-two elements in all, and has examined with painstaking care, both qualitatively and quantitatively, innumerable compounds. As far back as the beginning of the nineteenth century, his investigations led him to formulate two simple but important laws.

According to the first, if two or more elements unite to form a compound, they always do so in the same proportions. One* ounce of hydrogen will unite to form water, with eight ounces of oxygen, no more, no less; two ounces will unite with sixteen, one-half an ounce with four, and so on. In *any* quantity of water, there is always one part by weight of hydrogen to eight parts of oxygen. This is an example of the

* Strictly speaking the ratio is 1.008 to 8. Later it will be necessary to discuss the significance of the more exact ratio.

Law of Definite Proportions. The second law, which has to do with the manner in which the same elements combine to form different compounds, may best be illustrated by a concrete example. Hydrogen and oxygen unite to form not only water, but also another compound called hydrogen peroxide. In this substance there is one part by weight of hydrogen to sixteen parts of oxygen, from which it follows that the amount of oxygen which unites with a given amount of hydrogen in hydrogen peroxide is *exactly* double the amount which combines with the same quantity of hydrogen in water. This is an illustration of the Law of Multiple Proportions, which states that corresponding amounts of an element present in different compounds are always in the ratio of exact whole numbers.

Atoms and Molecules

These two "laws" are, in reality, nothing but statements of facts, and, as scientific discoveries go to-day, very old facts. Scientists, however, are only beginning their work when they have discovered generalized facts. They are interested primarily in finding an explanation of the facts. As far as the theme of our story goes, the importance of these laws lies in their simple explanation by the atomic theory of matter.

According to this theory, as it was first given in 1807-8 by the chemist Dalton, an element consists of ultimate, discrete, identical, invisible, and indivisible particles called atoms. Even in Dalton's time the general conception was not new, for atoms were almost as old as the proverbial hills, but never before had they been used as a basis of an hypothesis designed to explain facts in a quantitative way. There is a vast difference between the vague speculations about the structure of matter indulged in by the early Greek philosophers and a scientific theory capable of being tested by experiment. It is to the latter class that Dalton's theory belongs.

Dalton's atom is evidently the smallest piece of an element which can take part in a chemical reaction. When a compound is formed, the atoms of two or more different elements unite to form a *molecule,* the smallest piece of a compound which can exist. A molecule of common salt, for example, contains one atom of sodium and one atom of chlorine; a molecule of water contains two atoms of hydrogen and one atom of oxygen; and a molecule of sugar contains twelve atoms of carbon, twenty-two of hydrogen, and eleven of oxygen.

If, now, all the atoms of an element are identical and indivisible, it follows at once that there must be

the same proportions of different elements in any quantity of a compound. If a molecule of water contains two atoms of hydrogen and one of oxygen, two molecules will contain four atoms of hydrogen and two of oxygen, a million molecules will contain two million atoms of hydrogen and one million of oxygen. The relative amounts of the two elements in water must always be the same. And the second law follows just as readily. If a molecule of hydrogen peroxide contains two atoms of hydrogen and two atoms of oxygen instead of a single oxygen atom, as in water, then in any quantities of these two compounds containing equal amounts of hydrogen, the amount of oxygen in the one must be exactly double that in the other.

Throughout the nineteenth century evidence in favour of the existence of the atom became more and more conclusive. Both chemists and physicists found that a host of phenomena which can be observed and measured, agreed, both qualitatively and quantitatively, with predictions based on the atomic theory, or were adequately explained in terms of atoms and molecules. Of outstanding importance was work on the properties of gases. According to what is called the *kinetic theory*, in a gas there is a random distribution of molecules in rapid zig-zag motion, con-

stantly jostling each other and striking the walls of the containing vessel. With such a conception the physicist was able to show that the pressure exerted by the gas was due to this molecular bombardment of the walls; that a rise in temperature corresponded to an increase in the speed of the molecules—in fact, he could deduce experimental laws so readily that belief in the reality of atoms and molecules became a corner-stone in the theoretical structure of nineteenth-century physics. In the words of Clerk Maxwell, atoms were "the foundation stones of the universe." They are the bricks with which Nature constructs her infinitely varied types of architecture. A piece of stone, a flower, man himself, are but a collection of atoms.

Atomic Weights

If atoms are as real as nineteenth-century science seemed to indicate, there are certain inevitable questions to ask. How big are they? How much do they weigh? In considering the answers to these questions a clear distinction must be made between the absolute weight* of an atom and a set of numbers which gives

* Strictly speaking we mean mass. Since, however, weight is proportional to mass and since the phrase atomic weight is in general use, the more popular although less accurate word is used. For an exact definition of mass, see page 55.

only the relative weights of different kinds of atoms. As a result of many different experimental methods, it can be said with certainty that in a gram of hydrogen there are 600,000,000,000,000,000,000,000 atoms, and that if you place a row of them side by side, it would take about two million to cover a distance equal to the width of the dot over the letter i on this page. These are absolute values, that is, they are magnitudes expressed in terms of the standard units of length and of mass. At this stage of our story—indeed, throughout the greater part of it—we are interested chiefly in information about the relative weights of different atoms, and it is neither necessary nor desirable to discuss the methods used in obtaining absolute values.

Relative weights of different atoms are readily found from a knowledge of two things: (1) the proportions in which elements unite to form compounds; and (2) the number of atoms of each element in the molecule of a compound. Thus, if in water eight parts by weight of oxygen unite with one part by weight of hydrogen, and if a molecule of water contains one atom of oxygen and two atoms of hydrogen, then the atom of oxygen must be sixteen times heavier than the atom of hydrogen. A knowledge of the relative weights of two or more elements in a given com-

pound is purely a matter of chemical analysis and, as we have seen, is independent of any theory, atomic or otherwise. But a determination of the number of atoms in a molecule is quite a different matter, and a complete explanation would take us far afield from the main path of our story. Suffice it to say that this information is obtained when a principle, first enunciated by the Italian physicist Avogadro in 1811, is combined with the results of quantitative chemical analysis and with a knowledge of the proportions in which gases unite by *volume* rather than by weight. Avogadro's principle or hypothesis, which states that equal volumes of all gases under the same conditions of temperature and pressure contain the same number of molecules, was the extension of Dalton's Atomic Theory necessary to put the theoretical interpretation of chemistry on a solid foundation. Among other things it has shown that in the normal state of many elements, the atoms do not remain unattached, but unite, frequently in pairs (as in *diatomic* oxygen, hydrogen, nitrogen, iodine, etc.) to form molecules of the element; and, as we have briefly indicated, the principle has been an essential factor in the assignment of the number of atoms of each element in the molecule of a compound.

It is possible, therefore, to assign to all elements

numbers such that the weights of their atoms are in the ratio of the corresponding numbers. As we have seen, if we assign 1 to hydrogen, 16 must be assigned to oxygen, and the methods we have briefly outlined, show that, on the same scale, 14 must be assigned to nitrogen, 35.5 to chlorine, and so on.

These numbers are called *Atomic Weights* and the accurate determination of their values has been and still is of the greatest importance in science. In the advance of any science, certainly in physics and in chemistry, the necessary condition for progress is exact measurement. In the early development of any branch of a scientific subject, the accuracy is usually not high, but when tentative or rival theories are formed, they are tested by measurements which must be more and more accurate. Sometimes the fifth decimal place does not matter; sometimes it is the deciding factor in settling the merits of rival views. As will appear in due course, few better examples of the truth of this can be found than in the need for accuracy in atomic weights which exists at the present time.

The values of the atomic weights depend naturally on the number assigned to the element used as a starting-point. If, for example, 2 were assigned to hydrogen, all of the other weights would be doubled.

As a matter of fact, although originally the systen was built up by assigning to hydrogen the value 1 (ii which case accurate measurements show that thi atomic weight of oxygen is 15.87, not 16.00), ii modern usage all weights are assigned on the basi: of 16.000 for oxygen. The change in the scale wa: made because, although assigning 16.000 to oxyger makes the atomic weight of hydrogen 1.008, in thi case of many elements it gives more nearly exac whole numbers than on the old scale with hydroger equal to1.000. In Table III, at the end of the book in the fourth column, a list of atomic weights (foi a number of elements) is given.

A glance at this table will reveal a very importan fact. Although the atomic weights of many element: are nearly whole numbers such as 12.0 for carbor and 23.0 for sodium, others, such as 35.5 for chlorini and 118.7 for tin, are decidedly not. If all wer whole numbers or nearly so, it would be tempting tc conclude that, in some way, the atoms of all element: are made up of hydrogen atoms. This of course i: a denial of the original conception of the indivisibility of an atom, but before the days of exact determination of atomic weights, this was actually an hypothesis suggested, in 1815, by Prout, an English physician. Prout's idea did not bear fruit, because ac-

curate measurements showed how much the atomic weights of some elements depart from whole numbers. Before our story is finished, however, it will be seen that Prout builded better than he knew.

Since the last decade of the nineteenth century, it has been shown that the atom, far from being indivisible, has a complex structure; that all atoms of the same element are not identical; and that the atoms of all elements contain a few common constituents. In the development of these ideas atomic artillery has played an important part. Since, for the most part, the ammunition consists of electrified particles, and since the methods of projection are frequently electrical, in the next chapter a few elementary facts of electricity will be explained.

CHAPTER II

PROPELLING ELECTRIFIED PARTICLES

Two Kinds of Electricity

If a rod of ebonite or a stick of sealing-wax—a fountain pen will do if nothing else is available—is rubbed against wool or flannel, it acquires a peculiar property. When brought near shreds of dry paper, the rubbed rod attracts the little pieces. They stand on end and some may even jump into the air to meet the rod. Instead of paper any substance may be used, provided the pieces are small and dry. Frequently a little ball made of pith wood, a very light substance, is suspended by a silk thread. When the rubbed ebonite rod or sealing-wax is brought near the pith ball, the same strong attraction is observed.

This effect is due to the presence on the surface of the rod of a charge of electricity. The rod has been electrified by being brought into intimate contact with the wool or flannel and, as a result, has acquired the property of attracting light pieces of matter. The words electricity and electrified have their origin in

electron, the Greek word for amber, because as long ago as 600 B.C. Thales, the Greek philosopher, observed that amber when rubbed has this power of attraction.

If a dry glass rod is rubbed on silk, the glass acquiries the same property. It, too, will attract the pith ball or the light pieces of paper. It, too, has been electrified. But there is a very important difference between the electricity on the ebonite and that on the glass, a difference which must be made clear because it underlies most of the methods used in projecting atomic particles.

To explain this difference, we must again resort to a simple experiment. This time we take three rods, two ebonite and one glass, and electrify each in the way we have just described. If, now, we suspend one of the ebonite rods so that it is free to move, and then bring near it, first the other ebonite rod and second, the glass rod, we cannot fail to note a very remarkable difference in the two cases. The ebonite rod in our hand pushes the suspended one away from it, whereas the glass rod exerts a strong attraction. In other words the movable rod is repelled by one *which has been electrified in the same way*, but is attracted by a glass rod electrified by being rubbed against silk. The conclusion is inevitable. The kind

of electricity on ebonite (rubbed on wool) must be different from the kind on glass (rubbed on silk).

To distinguish the two kinds, Du Fay, a French scientist who discovered this fact at the beginning of the eighteenth century, used the names *resinous* and *vitreous*, but nowadays we call them *negative* and *positive*, and frequently use the symbols — and + to represent them. There is no special significance about the use of these more or less algebraic terms. Positive simply means the kind of electricity on a glass rod rubbed with silk; negative, the kind on a piece of ebonite or sealing-wax rubbed on wool or fur or flannel; and *we can scarcely over-emphasize the fact that the same kinds repel and unlike kinds attract.*

By bringing their surfaces together we can electrify many substances. Some will be found to have positive charges, that is, when brought near the suspended ebonite rod they will attract it; the remainder will have negative charges. With a little care another important fact can be verified. Of any two substances rubbed together, one always becomes positive, the other negative. Thus sealing-wax acquires a negative charge, wool or flannel a positive; or the glass rod is positive, but the silk negative. Presently we shall see that there is a very simple reason for this.

Speeding up Electrified Particles

Suppose, now, that we have two metal plates M_1 and M_2, mounted on insulated stands, somewhat as shown in Fig. 1, and that one plate has been given a strong positive charge, the other a strong negative. This may be done by repeatedly touching M_1 with a

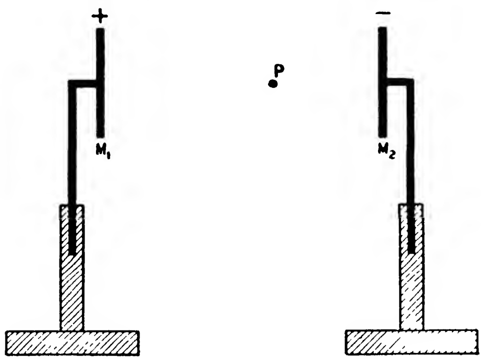

FIG. 1.—If the charged particle *P* has a positive charge it will move towards M_2 the negative plate; if a negative charge, toward M_1 the positive plate.

glass rod rubbed on silk, and M_2 with an ebonite rod rubbed on fur or flannel, but a better method consists in joining M_1 and M_2 to the terminals of certain electrical machines. Into the mechanism of electrical machines it is not necessary for us to go. Suffice it to state that whether it is a dynamo, or a static machine, or an induction coil, or even a dry cell and a storage battery, in all such devices there is a sepa-

ration of positive from negative electricity, positive appearing at one terminal, negative at the other. If, then, the plates M_1 and M_2 are joined to the terminals of an induction coil, a positive charge will be maintained on one and a negative on the other.

Now imagine that a small *electrified* particle, such as P in Fig. 1, is in the region between these charged plates. Because of its electric charge it will be repelled by one plate, attracted by the other, and if it is free to move and the force acting on it is great enough, it may acquire considerable speed before reaching the plate bearing the charge of opposite sign. Presently we shall see that single atoms may be electrified and projected at high speed by means of an arrangement similar in principle to the one we have been discussing.

Potential Difference and Voltage

In atomic artillery we are greatly interested in the magnitude of this speed which may be acquired when a particle is acted on by an electric force. This depends on several factors such as the mass of the particle, the magnitude of the force causing it to move, and the length of time the force acts, but the problem is essentially a mechanical one and it is not necessary to consider it in detail. There is, however, one factor which is so important and so widely used in atomic

artillery that we must try to make it clear. A simple analogy will perhaps help. When water tumbles over a falls, the speed acquired by a single drop (because of the force of gravitation acting on it) depends on the height from which is has fallen. The greater the height or the greater the difference in levels, the greater the speed of the drop. Moreover, from a knowledge of the difference in levels, a simple calculation gives the velocity acquired by a drop in falling that distance. For example, a drop which has fallen freely 25 feet has a speed of 40 feet per second; 36 feet, a speed of 48 feet per second; and so on.

In electricity there is a quantity very similar to difference in level. Just as a piece of ordinary matter falls from a high level to a low level because of the gravitational force acting on it, so *an electrified particle,* when set in motion by an electric force, moves from a place of high potential to low potential*; or, putting it in another way, a difference of potential is said to exist between any two regions, or any two conductors, if electric forces are present which will make an electrified particle move from one region to the other. This difference of potential is measured in

* This assumes that the charge on the particle is positive. If negative, it moves in the opposite direction.

volts. Between the wires which deliver electrical power to your house, there is a difference of potential in the neighborhood of 110 volts or possibly 220 volts; between the terminals of a single unit of the storage battery in your car, there is a potential difference of about 2 volts; and between the wires or rods which run to the two sides of an x-ray tube, there is potential difference which may be 100,000 volts or more.

When an electrified particle moves from a place of high potential to one of low, that is, through a difference of potential, the speed it acquires, if free to move without restriction, depends on the magnitude of this potential difference. Low differences mean low speeds, high differences, high speeds, just as in the case of falling bodies. If, then, in an arrangement like that of Fig. 1, we wish the particle P to move at high speed, two conditions must be fulfilled: (1) the potential difference between the plates M_1 and M_2 must be large; and (2) the particle must be able to move with but little obstruction. The first condition is realized by joining the plates to the high voltage terminals of an induction coil (or other electrical device) by means of which not only are positive and negative charges given to the plates, but also potential differences ranging from possibly 10,000

to 1,000,000 volts can be maintained. To realize the second condition, the plates M_1 and M_2 are placed inside a tube from which most of the air is removed. In the next chapter we shall explain in detail what happens when a high voltage is applied to such a tube.

CHAPTER III

ELECTRONS, THE LIGHTEST PROJECTILES

There are few people nowadays who are not familiar with the brightly coloured electric signs which adorn the main streets of towns, big and little. Not so many are aware that the colour is the result of an electric current passing through a gas contained in a long narrow tube. If you look closely at an electric sign, you will have no difficulty in seeing the glass tube, but you may not realize that in order to get the coloured light, a voltage must be applied between pieces of metal inserted in the walls of the tube. When this is done, a current passes through the gas. It is an example of the conduction of electricity through gases, a subject which was studied extensively during the last half of the nineteenth century, with far-reaching results. Let us look at some of them.

Cathode Rays

Consider a tube somewhat as represented in Fig. 2, where M_1 and M_2 are two metal plates—*electrodes* we shall now call them—joined to the terminals of

an induction coil, and T is a side-arm tube attached to a suction air-pump. If by operating the induction coil a high voltage is maintained between the electrodes and if the air is gradually removed from the tube, very beautiful effects are observed. A column of light extends from one electrode to the other, its appearance gradually altering as a better and better vacuum is obtained. At first there is a narrow, wavy

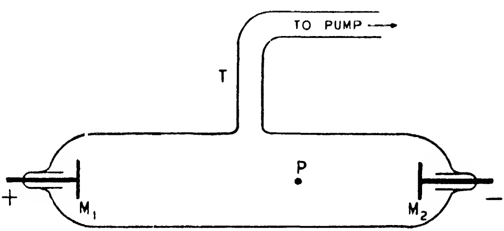

FIG. 2—When most of the contained gas is removed from the tube by means of a pump, an electrified particle P, if negatively charged, moves readily towards M_1, the positive electrode, but towards M_2, the negative electrode, if positively charged.

streak of light down the central part of the tube. This is followed by a diffuse luminosity which almost fills the whole tube, somewhat as in the electric sign. As the vacuum improves, alternate regions of light and darkness are observed. These in their turn disappear, the light becomes dimmer and dimmer, until all that remains is a faint streak apparently proceeding from the centre of the negative electrode or *cathode*, as it is usually called. At this stage the

vacuum is so good that perhaps only one hundred-thousandth part of the original amount of air remains in the tube.

This faint streak of light was the object of much study by the pioneer workers in this field. They showed that it was caused by a stream of something, to which the name *cathode rays* was given, which travelled in straight lines from the cathode. By taking a tube like Fig. 3, in which the positive electrode or *anode* is off to one side, it was found that the

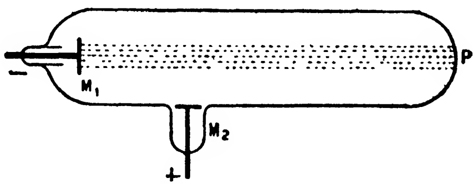

FIG. 3.—The dotted lines represent a beam of cathode rays which, in a tube with nearly all the contained gas removed, move in straight lines away from the neighborhood of M_1, the negative electrode.

cathode rays do not bend around to the anode, but continue straight on from the cathode until they strike the end of the tube in the neighborhood of P. Nothing is seen to strike, but the place where the rays hit the glass is revealed by a patch of fluorescent light. A variation of this experiment, first performed by the British physicist Sir William Crookes, provides a still more striking proof that cathode rays travel in straight lines. If a tube is taken similar to that illus-

trated in Fig. 3, but with the addition of an obstacle which can be interposed between the cathode M_1 and the end of the tube, a very sharp shadow of this obstacle is thrown on the end of the tube.

The nature of cathode rays was for a long time a debatable subject. Light travels in straight lines and casts sharp shadows, but so also do small particles moving at high speed. It is not surprising, therefore, that there were two rival views. According to one, cathode rays were some kind of ether disturbance not unrelated to light; according to the other, the rays were electrified particles. Eventually experiment settled the dispute—as it always does—and it became evident that the second view was the only one tenable.

Of the many experiments which proved this, we shall describe but one. It consists in using a tube like that shown in Fig. 4 in which M_1 is the cathode,

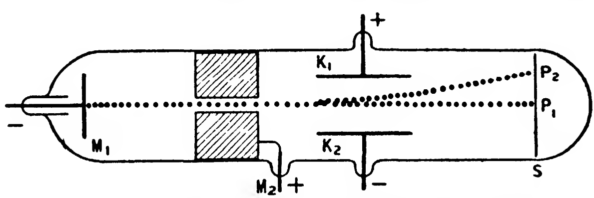

FIG. 4.—The dots represent a beam of cathode rays which, on emergence from a hole or tunnel in the *positive* electrode, pass between the metal plates K_1 and K_2. If plate K_1 is charged positively and K_2 negatively, the narrow cathode ray beam, instead of striking the screen S at P_1, is deflected to one side striking at P_2. This shows that cathode rays have a negative charge.

and in which M_2, the anode, is made of two discs each with a small hole through the centre or else is made in the form of a metal cylinder with a tunnel down the centre. Whatever the nature of cathode rays, when they strike an anode of this kind a narrow beam passes through these holes or down the tunnel and emerges on the far side. The beam, continuing on its way down the tube, strikes a screen S coated with a substance which glows when struck by cathode rays. A little patch of light P_1 is then observed on this screen. So far, this tells us nothing new about the nature of cathode rays, but the tube has one other feature. Between the anode M_2 and the screen S, the narrow beam must pass between two metal plates K_1 and K_2. Under ordinary conditions these have no observable effect on the beam. If, however, the plates are joined to the terminals of a battery so that there is a potential difference between them, with one plate positively charged, the other negatively, the patch of light moves from P_1 to P_2. In its passage through the electric field between the charged plates the beam of cathode rays has been deflected. There is only one conclusion. These rays must consist of a stream of electrified particles which are repelled by one plate, attracted by the other. Moreover, since the deflection is *towards* the positive plate and *away* from the negative, the particles must carry a negative charge.

This experiment was by no means the first to prove that cathode rays are negatively charged particles. It had been shown previously, for example, that a beam is deflected when passing between the poles of a magnet, a fact which leads to the same conclusion, although a more intimate knowledge of electricity is necessary to understand exactly why this is so. But the experiment with the charged plates was the climax of a series which left no doubt about the corpuscular and the electrical nature of cathode rays.

If this conclusion is accepted, certain questions at once suggest themselves. How big are these particles? How fast do they move? Are they all the same size? What electrical charge do they carry? By making measurements with tubes similar to that shown in Fig. 4, the answers to these questions were soon forthcoming. It is a simple matter to measure on the screen S the distance from P_1 to P_2, that is, to measure the amount the beam is deflected; and it should not be difficult to see that this depends on the very things we wish to know. To begin with, the greater the electric charge the particle has and the larger the voltage across the plates K_1 and K_2, the greater the force pushing the particle to one side. But heavy particles are not pushed aside as readily as light, nor fast particles as easily as slow, hence the amount of deflection depends not only on the force

acting on a particle but also on its mass and its speed. For the trained physicist comparatively simple calculations connect all these factors together, and from his calculations and observations, made with both electric and magnetic fields, the following information has been obtained.*

(1) The mass of a cathode ray is about 1/1846 of that of a hydrogen atom, hitherto the lightest particle known. Moreover, this mass is the same regardless of how the experiment is performed. The cathode in the tube may be made of iron, or of copper, or of silver, or of aluminum, or any other metallic substance; the gas in the tube before it was evacuated may have been ordinary air, or oxygen, or hydrogen, or carbon dioxide, or any other kind—in all cases the same result is obtained. All cathode rays have this same mass.† This was a startling discovery. At last a *prima materia,* a common constituent of all kinds of matter, has been found. The atom can no longer be considered uncut or uncuttable. It must contain particles with a mass nearly two thousand times less than that of the hydrogen atom.

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* By means of a tube like that shown in Fig 4 only the ratio of the charge on the cathode ray to its mass is obtained. To find each of these quantities separately the charge must be found by another experiment.

† See, however, page 56.

(2) Each cathode ray has exactly the same amount of negative electricity. It is such a small amount that 1,000,000,000,000,000,000 particles would have to be shot down a tube every second to give an electric current equal to that in an ordinary 20-watt tungsten lamp. Subsequent work showed that the amount of electricity on a cathode ray is a natural unit.

Outstanding among the pioneer investigations establishing this important fact is Millikan's oil drop experiment. Like a few other famous experiments it is beautiful in its simplicity. By means of an atomizer, electrified oil drops are sprayed into the space between two charged plates. A single drop ordinarily will fall slowly due to its weight, but, if it has a negative charge and the positive plate is above it, as in Fig. 5, the electric force acting on the drop will be in an upward direction, and may easily be adjusted until it exactly balances the downward pull of

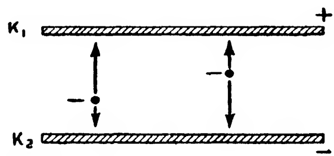

FIG. 5.—The principle of Millikan's oil drop experiment. If a drop (represented by the black dot) has a negative charge and lies between the two charged horizontal plates K_1 and K_2, the upper one being positive and the lower negative, the drop is attracted *upwards* by the electric forces. Since at the same time the force of gravity is pulling the drop *downwards*, it is possible to balance the two forces and hold the drop suspended.

the earth. The drop will then be balanced in space, somewhat like Mahomet's coffin. Calculations based on this experiment enable the exact charge on the drop to be obtained and show that *the charge is always equal to that on a cathode ray or to some multiple of it.* Smaller amounts have never been observed, and larger amounts occur in exact multiples of this fundamental unit of charge. Throughout this book, whenever we speak of so many unit charges we shall always have reference to this particular unit.

(3) The speed of cathode rays depends on the potential difference between the cathode and the anode in the same way as the speed of a falling body depends on the height from which it has fallen, and may be thousands of miles per second. For example, for a potential difference of 10,000 volts, the speed is about 37,000 miles per second, or about one-fifth of the velocity of light; for 100,000 volts, the speed is over 100,000 miles per second; and for a million volts, ninety-five per cent of the speed of light is obtained. Without question, cathode rays are high speed projectiles.

The Solar System Atom

Before looking at some of the results obtained—or the damage done—when a target is bombarded

by cathode rays, it is desirable to re-consider our views about atoms. As we have just seen, the discovery of cathode rays showed that atoms of all elements must contain negatively charged particles, a conclusion which was amply confirmed by subsequent work. These particles we now call *electrons*, reserving the name cathode rays for electrons which are shot down an evacuated tube. Electrons may be released from atoms in a number of different ways. A very common method consists in heating a metal to incandescence, in which case electrons evaporate from the metal, or, to be more scientific, there is a *thermionic emission* of electrons. In a radio tube, for example,

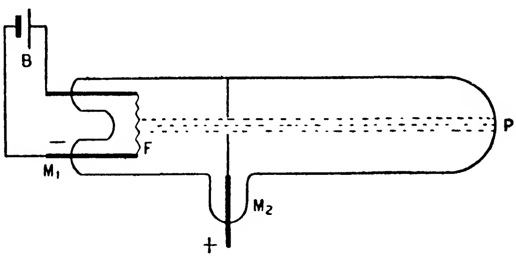

FIG. 6.—A simple electron gun. Electrons are liberated from a fine wire F which is heated by being included in an electric circuit with the battery B. By applying a voltage between the wire and the electrode M_2 in such a way that M_2 is positive, the electrons are shot from the filament, across the tube through the hole in this electrode.

the filament which you sometimes can see glowing, is heated to obtain a supply of electrons. If, therefore, an evacuated tube is made like the one shown in

Fig. 6, where the cathode of Fig. 4 is replaced by a wire* F heated to incandescence by passing an electric current through it, a beam of cathode rays is shot down the tube when the filament is joined to the negative terminal and the anode to the positive terminal of an induction coil. Such an arrangement constitutes the essential features of what is sometimes called an *electron gun.*

The new atom which contains electrons must have a structure far from simple. Since an atom as a whole exhibits no electrical charge it must contain enough positive electricity to neutralize the negative on the electrons. What does it look like and where is the positive electricity? Can we form a mental picture of it? The answer to these questions has not always been the same, but for a number of years it has been possible to visualize a model atom which has been extremely fruitful in explaining and interpreting many facts. This atom consists of a positively charged core or *nucleus* accounting for almost the whole of its mass, together with a number of electrons *whose total negative charge exactly equals the positive charge on the nucleus.* So small are both nucleus and electron that if an atom were enlarged to be the

* Frequently the wire is coated with a material like lime or calcium oxide which liberates electrons copiously when the wire is heated.

size of a balloon 60 feet in diameter, the nucleus and each electron would not be much bigger than a grain of sand. On this view the atom is a miniature solar system with the electrons revolving about the nucleus much as the planets revolve about the sun. The atomic theory reduces all matter to a pile of particles. We see that it is a very porous pile, tiny grains in a sea of empty void.

To distinguish one atom from another, two quantities must be known: (1) the atomic weight or the number proportional to the mass of the atom; (2) the *atomic number.* One or two concrete examples should make clear the meaning of atomic number. There is overwhelming evidence that in the atom of hydrogen, the lightest element, there is but one electron, with its unit negative charge, moving about the nucleus with an equivalent positive charge; in helium, the next lightest element, there are two electrons and the nucleus has two units of positive electricity; in lithium, the third lightest, there are three electrons and three positive unit charges on the nucleus; and, to give one other example, in the mercury atom, there are eighty electrons and the nucleus has eighty units of positive electricity. The atomic number is just the number of unit positive charges carried by the nucleus—which, of course, is the same thing as the number of elec-

trons in the normal atom. Hydrogen, then, has an atomic number of 1, lithium of 2, helium of 3, and mercury of 80. In modern physics the atomic number is of even greater importance than the atomic weight because the chemical properties of an element depend on the number and arrangement of the electrons surrounding the nucleus, and this depends on the atomic number.

Ionization

Since negative electricity attracts positive, each electron is strongly attracted by the nucleus. Indeed, if it were not for its motion, the electron would "fall into" the nucleus. By exerting a pull outwards, however, it is possible to remove an electron completely out of the atom away from the attraction of the nucleus. When that has been done, the nucleus has one unit of positive electricity in excess of the amount necessary to neutralize the negative charge on the remaining electrons, and we have what is called a positive atom-ion, or more often, just a *positive ion.* Sometimes two electrons are removed from the atom, and we then have a doubly-charged positive ion. The atom in each case is said to be *ionized*, and the means by which the electron or electrons have been removed are called ionizing agents. X-rays, gamma rays from

radium, and fast moving electrified particles are examples of such agents, with some of which we shall have to deal later. The electron which has been removed from an atom does not always remain in solitary state, but frequently attracts to it a neutral molecule or atom, or possibly several of them, forming a negative ion.

On this view electricity is never created, but is of the very essence of matter. When the ebonite rod is rubbed on wool, little forces (which we do not understand any too well) are brought into play which cause electrons to pass from the wool to the rod. For every million electrons gained by the rod, the wool loses a million. Consequently, whenever the rod acquires a million units of negative electricity, the wool, having a million positive units unbalanced by the electrons it has lost, acquires an equal positive charge.

A battery or a dynamo is not a means of creating electricity, but a device which separates positive from negative, with a resulting potential difference between its terminals. When a current flows in a circuit, it is simply a movement of electrical charges,—sometimes electrons only; sometimes negative ions in one direction, positive in the opposite.

Electron Bombardment

Electrons have been used as projectiles in a great variety of ways and much information has been gained in the process. A whole book might be devoted to this subject itself, but in this chapter we shall limit ourselves to a short summary of the more interesting effects.

To begin with, the sudden stoppage of cathode rays or high speed electrons gives rise to x-rays, the invisible light with which most people have some familiarity. In x-ray tubes an electron beam impinges on a target of metal and the spot struck by the beam is the source from which x-rays spread out. We cannot see this flight of tiny electrons, but the heat developed at the target is very real evidence of the bombardment. So hot does the target become that in x-ray tubes special means must be taken to prevent too great a rise in temperature. It is not difficult to find an old x-ray tube with a target having a little hole at the spot where the rays had impinged. The intense local heating was great enough to melt the metal at this spot. The heat developed by the bombardment of high speed cathode rays has actually been used as the basis of a small vacuum furnace, in which the specimen to be heated is placed inside the cathode ray tube.

In striking contrast to the heating effect of fast cathode rays is the fact that they can actually pass through a thin sheet of metal without doing any damage. In war the object of shooting projectiles is to destroy the target. As we have seen cathode rays can do that, but they can also pass right through a piece of matter and leave it intact. It is true the piece must be very thin*, but the effect is none the less real. Strangely enough, this observation was made before the true nature of cathode rays had been discovered, by Hertz in 1892 and by Lenard in 1893, both German physicists. The phenomenon was examined in detail by Lenard, whose name is now used to describe a cathode ray tube with a metal window at one end thin enough to allow the electrons to emerge into the outside air. Sometimes such tubes are also designated Lenard-Coolidge, because more recently Coolidge, of the General Electric Research Staff in Schenectady, N. Y., has experimented with them using potential differences of the order of a million volts —a value which gives the electrons a very high speed.

Tubes of this sort lend themselves to the examination of the effect of bombarding with electrons all sorts of substances placed in the open air outside the window. Thus Coolidge and other workers have found that, under the action of these cathode rays

* Of the order of one or two thousandths of an inch or less.

outside the tube, yeast, ergosterol, and a few other substances produce vitamin D; that new species may be originated in plants and animals; that changes in colour may be brought about in glass and other substances; and that it is possible to distinguish natural from artificial sapphire by the difference in their response to the rays.

Ionization by Collision

The ability to ionize a gas or a vapour through which it is passing is another important property of a rapidly moving electron. If moving quickly enough, an electron may pass right through an atom leaving it unharmed; if moving very slowly, the electron may not have enough energy to do any damage; but over a wide range of speeds, it will remove electrons from many of the atoms which lie in its path. As we have seen, whenever an atom loses an electron it becomes a positive ion. Hence the path of a fast electron is marked by a trail of ions.* This production of ions by a moving particle is one of the commonest ways of making a gas conducting. In the next two chapters we shall study this method of ionization more in detail.

* See page 64.

CHAPTER IV

HEAVIER PROJECTILES—POSITIVE RAYS

Before we can have a current between two electrodes in a tube containing a rarefied gas, the gas must be ionized, because this current, as we have seen, is nothing but a stream of positive ions in one direction, and negative ions and electrons in the opposite direction. The creation of these ions results from ionization by collision and depends on the fact that at all times there are present in air a few stray ions.* Consequently when a potential difference is first applied to the electrodes of such a tube, these stray ions are set in motion, and, if a partial vacuum has been created so that they can move some distance without obstruction, they acquire enough energy to ionize atoms by collision. As the electrons released from the atoms in their turn are speeded up, more ions are created, and in a very short time there is a rapid accumulation of ions and a current passes,

* One of the chief causes of these stray ions is probably cosmic rays, a subject discussed in Chap. VII.

positive ions moving towards the cathode, negative ions and electrons towards the anode. If a stream of cathode rays is wanted, the vacuum is made so good that the liberated electrons, largely formed in the neighborhood of the cathode, move the full length of the tube with little obstruction. Fig. 7 is an attempt to depict the state of affairs at somewhat higher pressures, when the tube is filled with light, as in the electric sign, and when throughout its length numerous positive and negative ions are to be found.

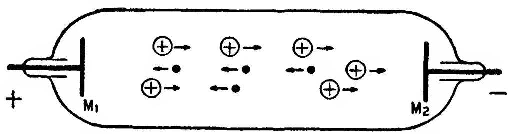

FIG. 7.—In a tube containing a little gas at not too low a pressure numerous positive and negative ions move in opposite directions, positive towards the negative electrode M_2, negative towards the positive electrode M_1.

The existence of a stream of positive ions may be shown very beautifully by using a tube in which holes are made in the cathode, not the anode, somewhat as shown in Fig. 8. At suitable pressures, in B, the portion of the tube beyond the cathode, a narrow beam of light is seen as a continuation of each hole in the cathode, an observation made in 1886 by the German scientist Goldstein. At that date, it must be remembered, neither electrons nor ions had been discovered, and Goldstein, not knowing the true nature

of the rays passing through the holes in the cathode, appropriately called them *canal* rays. It remained for another German, Wien, in 1898, to show that canal rays, if made to travel through either an electric or a magnetic field, were deflected to one side, just like cathode rays, and so were electrified particles. These are three very important differences, however, between canal and cathode rays.

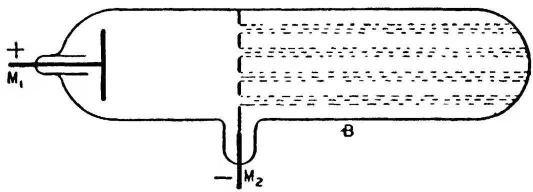

FIG. 8.—Positive ions pass through the perforations in the negative electrode M_2 and at suitable pressure give rise to coloured streamers, represented in this diagram by the dotted lines.

(1) The direction of the deflection of canal rays in a tube like the one shown in Fig. 9 where a narrow beam passes between electrified plates, is *towards* the negative plate, not away from it as in the case of cathode rays. Canal rays, therefore, must be positively charged. This, of course, is just what one should expect, for they are nothing but the stream of positive ions which come up to the cathode and passed through its perforations. In fact, J. J. Thomson, who was one of the pioneer workers with these rays, changed their name to positive rays.

(2) It is much more difficult to deflect canal rays, stronger electric and magnetic fields being necessary to do so. As a matter of fact, Goldstein tried unsuccessfully to deflect them with a magnetic field. The reason for the difficulty in deflecting the rays is due to the much heavier mass of an ion than a cathode ray, because as we pointed out when dealing with the deflection of cathode rays, the heavier a particle is, the harder it is to push it out of its path.

(3) Measurements of the same kind as used in cathode-ray deflection tubes show that canal rays are of atomic size, but that their masses are not always the same. If the gas in the discharge tube is changed, the masses of the canal or positive rays are altered also. Again this is to be expected once we realize that positive rays originate in the positive ions in the discharge tube. If a tube contains hydrogen, then ionized atoms of hydrogen will pass through the hole or holes in the cathode; if oxygen, then oxygen atom-ions; and if there is a mixture of these two gases, in the canal ray beam there will be both oxygen and hydrogen ions.

A New Method of Chemical Analysis

If a positive ray beam containing a mixture of ions of different masses passes through an electric and a

magnetic field, it will be sorted out into its components. This is the principle of the positive ray method of chemical analysis which was first used by J. J. Thomson with such remarkable consequences that it is necessary to understand it clearly. In the method originally used by Thomson a tube was built somewhat as shown in Fig. 9. The rays pass through a fine tunnel in the cathode C and on emergence travel

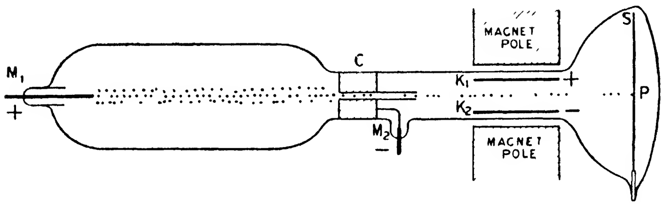

FIG. 9.—A simple tube for the analysis of a beam of positive rays. The dots represent positive ions, some of which pass through the tunnel in the centre of M_2, the negative terminal. On emergence from the tunnel the narrow beam normally strikes a screen S at the spot P. If an electric field is maintained between the plates K_1 and K_2 and at the same time the tube is placed between the two poles of the magnet, the heavier ions are then deflected by both fields less than the light, and the beam is sorted out into its components. Patterns on the screen like Fig. 10, Plate I, are obtained.

across a highly evacuated region until they strike a screen S (or a photographic plate) at the end of the tube. When the screen is coated with certain materials there is a fluorescent spot of light at the place P struck by the rays; or if a photographic plate is used the rays affect it as much as light does and on development an image of the spot is obtained. In Fig.

10, Plate I, an original photograph taken by Thomson and reproduced with his kind permission, the spot at the centre was caused by such a narrow beam of undeflected rays.

If, however, the beam passes between the electrified plates K_1 and K_2, that is, through an electric field, and at the same time, between the poles of a magnet, there is a sorting out of the rays or ions. When the fields are so arranged that one pushes the particles vertically, the other horizontally, then all particles of the same mass and same electric charge, regardless of their speed, strike the screen or the photographic plate along a curved line. It is much the same as if bullets of different sizes were emitted by a machine gun and on their way to a target were acted on by two forces, one pushing them sideways, the other up or down. With such an arrangement all the bullets of one size would hit the target along one line, of another size along a different line, and so on. If a positive ray beam contains singly-charged atoms of hydrogen, of oxygen, and of nitrogen there is a curved line on the plate corresponding to each kind of atom. In Fig. 10, Plate I, the beam which was analyzed in this way, has given rise to four such curved lines, the line marked 1 arising from singly charged hydrogen atoms, that marked 2 from singly charged

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Readers familiar with photographs of optical spectra will note the similarity. Just as a beam containing a mixture of different kinds of light on passing through a prism is spread out into a spectrum showing all its components, so the beam of positive rays by this method is separated into its constituents. It is not surprising that the apparatus used in the analysis is called a *mass-spectrograph,* and the photograph, in which each line corresponds to an ion of a definite mass, a *mass spectrum.* By measuring the separation of the lines along such a spectrum, an accurate comparison of masses and hence of atomic weights, may be made.

Discovery of Heavy Water

The story of how such measurements led to the discovery of heavy water is one of the most fascinating in modern physics. It begins with the analysis by Thomson in 1912 of the contents of a discharge tube containing small quantities of the rare gas neon, an element of atomic weight 20.2. On his plates he obtained not only a curve corresponding to an atomic weight of 20, but also one corresponding to atomic weight 22. Although there was no known element with the latter atomic weight, the evidence suggested that neon was responsible for both lines. In 1919,

Aston, who had resumed his work after the Great War, showed that there was no doubt about this conclusion. *The element neon was a mixture of two groups of atoms, one of atomic weight 20, the other of atomic weight 22, mixed in such proportions that they gave the value of 20.2 determined by chemical means.*

It will be recalled that according to Dalton's Atomic Theory the atoms of an element are identical. Here was unmistakable evidence that an ordinary element might have two kinds of atoms, of different atomic weights, but with the same chemical properties. As a matter of fact it was easy to accept this conclusion because previous investigations had shown that in unstable radioactive elements, the same phenomena occurred. In the field of radioactivity scientists had become familiar with groups of two or more elements whose atoms have the same number of electrons and identical chemical properties, but different masses. Indeed, in 1913 Soddy, one of the pioneer workers in radioactivity, had coined the name *isotope* to designate each member of such a group. The Thomson-Aston discovery was none the less of extreme importance because it showed that isotopes could exist in ordinary, that is, non-radioactive elements. With improved forms

of mass-spectrographs, it soon became evident that isotopes were the rule, not the exception, as a glance at Table III, at the end of the book, will show. In the element tin, for example, whose atomic weight is usually given as 118.7, there are no less than ten isotopes, with masses ranging from 112 to 124. Many of these are discernible in Fig. 13, Plate I.

It is important to realize that each of these isotopes corresponds to the element tin. Although the masses are different, *the atomic number, that is, the number of unit positive charges on the nucleus or the number of surrounding electrons in each is exactly the same, namely 50.* Since the chemical properties depend on this extra-nuclear structure, the isotopes cannot be separated chemically. Each isotope belongs to the element tin. It is, therefore, not the mass of an atom which tells you its name, but its atomic number. The distinguishing label of tin is its atomic number 50; of silver, its atomic number 47; of sodium, its atomic number 11; of mercury, its atomic number 80; and so on. We may even have different elements with atoms of the same mass. For example, the metallic element calcium with atomic number 20 has an isotope of mass number 40, and so has the gaseous element argon, of atomic number 18.

If neon has two groups of atoms of mass numbers 20 and 22*, what, it may be asked, is the atomic weight of this element? Can this result be reconciled with the atomic weight of 20.2 determined by chemical means? In chemical reactions the groups of isotopic atoms are not separated and the atomic weight determined chemically is an average value based on combining weights. To obtain the same average value from mass-spectrograph data we must know the relative amounts of each isotope. Once this information has been obtained it is just a matter of simple arithmetic to find the average atomic weight. If in a basket there are a number of grapefruit each weighing 10 ounces and an *equal* number each weighing 12 ounces, the average weight of each grapefruit in the basket is 11 ounces. If, however, most of the grapefruit in the basket weigh 10 ounces, only a few weighing 12 ounces, then the average weight is nearer 10 than 12, and it is not very difficult to work out the exact average if we know how many of each kind there are. In the same way average atomic weights are calculated from the isotope values given by the mass-spectrograph when we know the relative numbers of the different kinds. This information is

* The most accurate results show that there is a faint third component of mass 21. This may be seen in Fig. 11, Plate I.

readily obtained from the degree of blackening of the mass spectrum lines on the photographic plate, because the larger the number of ions which strike the plate, the blacker or the denser the image. Neon photographs, for example, show that the 20 component is 9 times more dense than the 22. For those who like arithmetic, it will not be a hard problem to show that the average atomic weight is 20.2.

The mass-spectrograph, therefore, has provided a method of obtaining atomic weights *entirely independent of the old-established chemical means.* If both methods are reliable, values obtained by the two methods should agree. In 1929, the agreement in fact was remarkable, the difference between corresponding values being only about 1 part in 10,000. In that year, however, it was shown that oxygen, which hitherto had been considered an element with only one isotope, of mass 16, had isotopes 17 and 18 present in small quantities. This meant that if the whole system of atomic weights is based on the assignment of 16.000 to the main isotope of oxygen, the average atomic weight of oxygen (the value based on all its isotopes) is slightly greater than 16.000; or conversely, if the *chemical determinations* of atomic weights are continued to be given in terms of 16.000 for oxygen, then the values for all other ele-

ments should be slightly less than those determined by the mass-spectrograph method. The correction to be made is slight, but it was enough to indicate a disagreement between the atomic weights of hydrogen, as determined by the two methods, which was just greater than possible experimental errors. Birge and Mendel, American physicists, suggested that the lack of agreement might be due to an undetected isotope of hydrogen of mass number 2. Urey, Brickwedde, and Murphy, American scientists also, set out to look for such an isotope spectroscopically, and in 1932 announced the discovery of heavy hydrogen or *deuterium*, of mass number 2. In a tank of ordinary hydrogen there is only one part of the heavy variety to several thousands of the light, but after the original discovery of deuterium, means were soon found of increasing its concentration, and eventually of completely isolating it.

Had it been just another new isotope, there would have been nothing very startling about the discovery of deuterium. As it was, it created a stir in scientific circles the world over, and in a very short time gave rise to a wealth of researches in chemical and physical laboratories. The reason is not far to seek. In so far as the positive charge on the nucleus and the number of extra-nuclear electrons are concerned, two isotopic atoms are exact twins and cannot be dis-

tinguished by any differences in properties which depend on these factors. If the ratio of the nuclear masses is nearly unity, as in chlorine with its isotopes 35 and 37, it is only by refined means that very slight differences depending on this change of mass can be detected. When, however, the masses differ as much as they do in the two isotopes of hydrogen, that is, in the ratio of 1 to 2, differences in their properties are easy to detect. In both physics and chemistry, therefore, the discovery of heavy hydrogen was followed by hundreds of investigations, all seeking to find out differences in the properties of all sorts of compounds when ordinary hydrogen is replaced by deuterium.

Outstanding among these researches were those dealing with heavy water. Ordinary water, it will be recalled, is a union of oxygen and hydrogen. Heavy water is the corresponding compound when deuterium replaces hydrogen, or if you like, when the hydrogen isotope 1 is replaced by isotope 2. You cannot distinguish the two kinds of water by looking at samples of each, but there are decided differences in their properties. Common water freezes at 32° Fah. and boils at 212° Fah.; the corresponding temperatures for heavy water are 38.8° Fah. and 214.5° Fah. Common water satisfies thirst, but it would not be wise to drink the new kind, although Klaus Hansen

of Sweden drank one-third of an ounce without injury. In any case, even if it were safe to drink it, few people could afford to do so, because it is worth about $50.00 an ounce.

The Proton

We have seen that the sorting out of atomic projectiles has led to a physical method of determining atomic weights, to the discovery of the existence of isotopes in general, and of heavy hydrogen in particular. Of even greater importance for the development of physics is the use of the mass-spectrograph for the accurate measurement of the masses of all isotopes, in terms of the number 16.0000 assigned to the main isotope of oxygen. Hitherto we have been using whole numbers,—the so-called *mass numbers,* 35 and 37 for chlorine, 1 and 2 for hydrogen, 20 and 22 for neon, 16, 17, and 18 for oxygen—as the values of atomic masses, without any explicit reference to their *exact* values. Now with the improved modern instruments, measurements of the displacement of the isotopic lines on a mass spectrum plate may be made to a high degree of accuracy. The results of such measurements show that in all cases, masses of isotopes are *very nearly* whole numbers. The few values given in Table I will illustrate the point.

TABLE I

A Few Exact Values of Isotopic Masses in Terms of Oxygen[16] = 16.0000

Element	Mass Number	Mass
Hydrogen	1	1.0081
Deuterium	2	2.0147
Helium	4	4.0040
Lithium	6	6.0170
Lithium	7	7.0182
Beryllium	8	8.0080
Boron	10	10.0160
Boron	11	11.0128
Carbon	12	12.004
Nitrogen	14	14.0075
Oxygen	16	16.0000
Neon	20	19.9986
Aluminum	27	26.9909
Argon	40	39.9754

An immediate consequence of this important general result was the revival of Prout's hypothesis in a modified form. Because of the large departure from whole numbers of the atomic weights of some elements, Prout's suggestion that all atoms might in some way be built from hydrogen atoms had never been given very serious attention. With the discovery of the "nearly whole number rule" for all isotopes, it was inevitable that the hydrogen atom, or more accurately its nucleus called the *proton*, should be

considered as an ultimate unit in the building of more complex atoms. At any rate, serious attention was given the theory that the nuclei of all atoms, in some way, are made of protons, with their positive charges, and negatively charged electrons. Note that this is a step still further away from the identical, indivisible atoms of Dalton, for it means that even the nuclei of atoms (except hydrogen) must be complex—an idea for which ample preparation had been made by researchers in radioactivity, as we shall see in the next chapter.

Equivalence of Mass and Energy

The hypothesis that protons and electrons are the bricks in atom-building, like all others, must pass a quantitative test. Let us apply one to the atom helium, whose atomic mass is 4.004. According to the proton-electron theory, the nucleus of the helium atom must contain 4 protons*, each of mass 1.008. But

$$\begin{array}{lr} \text{mass of 4 protons} = 4 \times 1.008 = & 4.032 \\ \text{mass of helium atom} & \underline{4.004} \\ \text{therefore, the difference} = & .028 \end{array}$$

* Since the atomic number of helium is 2, that is, since its nuclear charge is 2 positive units, the nucleus must also contain 2 electrons to counterbalance 2 of the positive charges on the protons. As the mass of an electron is 0.00055, the significance of the above calculation is not altered by neglecting it.

This simple piece of arithmetic shows that *when four protons unite to form the nucleus of a helium atom, their total united mass is less than it was before they came together*, and the measurements are far too accurate to ascribe the difference to experimental error. .028 unit of mass have been lost. Two and two do not always make four, it would seem. To explain the reason for the discrepancy, we must make a digression.

Two of the foundation stones in the nineteenth-century structure of physics and chemistry were the laws of conservation of matter and conservation of mass. According to the first, the sum-total of matter in the universe is always the same. Mix two granules of one chemical with two granules of a second, and, no matter what the resulting product or products may be, there will always be exactly four granules in all. Nobody doubted that two and two make four where matter was concerned.

The conservation of mass is not quite so simple, for contrary to a statement which used to appear in some text-books of science, mass is *not* quantity of matter, nor is mass the unique possession of matter. It is rather a measure of the inertia of a piece of matter, of what we might call its laziness. The harder it is to set a body in motion, the greater is its mass;

or the harder it is to push a projectile out of the path in which it is moving (as in positive ray analysis) the greater the mass of the projectile. At one time the physicist believed that every substance had a constant mass, but gradually he learned to think otherwise. Before the nineteenth century was over, J. J. Thomson had shown theoretically that the mass of an *electrified* body should vary with its speed, or that there is such a thing as electromagnetic mass. This deduction was verified experimentally by Kaufmann, a German scientist, who showed that the faster an electron moves, the harder it is to push it out of its path and therefore the greater is its mass. It then became necessary to think of particles capable of having different masses under different conditions.

Still more revolutionary ideas about mass follow from a law formulated by Einstein. According to this law, which is one of the consequences of the theory of relativity, (1) *an increase in the energy of a body represents an increase in mass*, and (2) *every form of energy has an equivalent mass.* If you are running, you possess energy of motion, and on that account your mass is just a little bit more than when you are at rest. It sounds fanciful, and the effect is so small that you could not detect the increase in mass due to the energy of motion of a 200-ton locomotive

moving at 60 miles an hour, but it is none the less real. The equivalence between mass and energy has been verified by an experiment which we shall describe after we have made the acquaintance of other atomic projectiles, and is now one of the most fundamental conceptions in modern physics. Its validity is not questioned. *Inert matter has mass, but so has energy.*

If we accept Einstein's idea, the problem of the lost mass when protons come together has a ready solution. During the process in which the four protons were being fused together to form the nucleus of a helium atom, energy was released, and the 0.028 unit are just the equivalent mass of this energy. Matter disappears, energy is born. If matter can be turned into energy, then the law of conservation of matter can no longer be maintained; and if the same particle can have a mass which varies with its speed, it would seem *as if* the law of conservation of mass were equally untenable. Is there then, nothing which endures in physical science? There is, and it is energy. There was a third foundation stone in the nineteenth century and that was the law of conservation of energy. This has stood like a rock of Gibraltar unshaken by all the revolutions of the twentieth century. In all the transformations of one kind of

energy into another, none is ever lost. Value given for value received applies without exception to all energy transactions. In science you never get something for nothing. In every energy exchange the amount of one kind developed is exactly equal to the amount of another kind expended. Every now and then the validity of this law has been threatened, but never has it been overthrown. It is a bed-rock principle in physical science.

When this principle is coupled with Einstein's law of the equivalence of mass and energy, it will be seen that we need not discard the law of conservation of mass. Conservation of one implies the conservation of the other. If there is no loss of energy in an exchange, there can be no loss of mass. The increased mass of a fast moving particle, simply represents the energy of motion it has acquired because work was done on it *by some external source.* When the particle comes to rest on striking a target, it loses this extra mass, because the energy equivalent is passed on the target or to the surrounding medium.

When four protons come together and 0.028 unit of mass disappear, they are not lost, but re-appear as the mass equivalent of the released energy. 0.028 unit of inert matter, however, no longer exist, and

there is more than a suggestion that matter can be annihilated and turned into energy. Destroy matter and gain energy. The idea has amazing possibilities. Shall we ever be able to control atom-building and *harness* the energy released? Shall we ever be able to wipe out even a few grains of matter and utilize the corresponding energy? If we could, the annihilation of a pellet of coal weighing an ounce would release enough energy to provide the electric power requirements of a quarter of a million people for one year—assuming a monthly bill of $5.00 a month, and a rate of 2 cents per kilowatt-hour. To a race whose very existence depends on energy supplies, these questions are of tremendous importance. To them we shall return when considering more fully the bombardment of the nucleus of an atom.

CHAPTER V

NATURE'S PROJECTILES

The Discovery of Radioactivity

To give protons or any kind of positive ions the high speed necessary for atomic bombardment, either extremely high voltages must be used, or else certain special devices which apply a moderate voltage at regular intervals until the desired velocity is attained. Scientists, however, are not entirely dependent on their own devices for getting suitable projectiles, because in at least two ways Nature has provided them with a supply of ammunition. One supply is obtained from radioactive substances, the other from cosmic rays.

The middle of the last decade of the nineteenth century was one of the most fruitful periods in physical science which has ever existed. Within two or three years, the electron, x-rays, and radioactivity were all discovered. These were by no means independent discoveries because in science, as in life, one thing often leads to another. A good example of this

is found in the discovery of radioactive substances. The walls of gas x-ray tubes strongly fluoresce and in the early days it was not unnatural to associate the origin of these invisible rays with the fluorescence. With this idea in mind, Becquerel, a French scientist, tried to see if certain compounds of the element uranium would emit x-rays after being made to fluoresce by exposure to light. He was rewarded by finding an invisible radiation, but was soon able to show that it had nothing to do with x-rays. The uranium compound in its normal state, that is, without any stimulus by light or by anything else, was found to emit something which passed through a sheet of black paper and affected a photographic plate behind the paper. This emission, moreover, was perfectly spontaneous. Neither heat nor cold could start or stop it. It was a natural property of the compound. Radioactivity had been discovered.

This original discovery was followed by rapid developments and it was not long before it was found that residues of pitchblende, one of the ores in which uranium is found, were much more radioactive than pure uranium compounds themselves. Soon afterwards Madame Curie, the Polish wife of a French physicist, with the assistance of her husband, isolated *polonium* and *radium,* two substances possessing

radioactive powers in a remarkably high degree. Radium was shown to be an element of atomic weight 226 with chemical properties similar to the stable element barium.

It is, however, with the nature of the radiations emitted by a radioactive substance that we are specially concerned, not with its chemical properties. The radiations, whatever they are, have three outstanding properties. They ionize the air, or any gas, through which they pass; they affect a photographic plate like light or x-rays or positive rays; and they cause fluorescence when they strike certain substances. The ionization effect will detect such a small quantity of a radioactive substance that it has been of great importance throughout the whole development of the subject; the photographic effect led to Becquerel's discovery; and the ability of the rays to excite fluorescence is probably familiar to most people because of the radium-coated watch hands which may be seen in the dark.

Alpha, Beta, and Gamma Rays

But what are these radiations and why do they have these properties? To find out, what more natural than to make the radium rays pass through a magnetic field and see if they are deflected as cathode

rays are. When this was done it was found that the rays were separated into three groups. One group, to which the name *beta* rays was given, was deflected easily and in a direction which showed them to be negatively charged particles. A second group, which required a very strong magnetic field to deflect them at all, was bent in the opposite direction and so must be positively charged. These were called *alpha* rays. The third group, *gamma* rays, could not be deflected at all by the most powerful fields, and evidently does not consist of electrified particles at all. Actually the gamma rays are of the same nature as x-rays, but for the present they need not concern us. Beta and alpha rays we must examine in some detail.

Beta rays are nothing but electrons shot out of radioactive substances with velocities which vary, but may exceed nine-tenths of the velocity of light, or 160,000 miles a second. To acquire a speed equal to the fastest beta ray which has been observed —ninety-nine percent of the velocity of light—a cathode ray would have to fall through a potential difference of over three million volts. It is little wonder, then, that fast beta rays pass through sheets of metal several millimetres thick and traverse as much as ten feet of air before they are stopped. As they shoot along through air, their path is marked by

a trail of ions. We cannot see an ion any more than we can see an electron, but it is possible by a very beautiful experiment, first performed by C. T. R. Wilson at Cambridge University, to make each ion the centre of a little drop of water which reveals its presence in unmistakable fashion.

The idea on which the experiment is based, is really a very simple one. When air is laden with moisture, a fog will form much more readily if dust is present than if the air is dust-free. It has been said that if all the sooty smoke which pollutes the air over the city of London could be consumed or in some way prevented from leaving chimneys, fogs would be neither thicker nor more prevalent over that city than elsewhere in England. The suggestion is based on sound physics, because water condenses readily when little particles of dust or dirt are present to act as nuclei around which drops can form. Now Wilson showed that *ions also act as nuclei for the formation of water drops.* In the actual experimental arrangement ions are formed by an ionizing agent in moisture-laden, but dust-free air, the air is allowed to expand suddenly and thereby be cooled, the water condenses on the ions, and a flash of light enables a "cloud-track" photograph to be taken. *For each invisible ion, a visible drop appears.*

In Fig. 14, Plate II, the path of a beta ray moving too quickly to be deflected out of its path by collisions, is marked by the straight line of little white dots. Each dot, it must be realized, represents a drop of water and hence an ion. On the same photograph the irregular curves are due to slower electrons which are easily turned aside. The smooth curves of Figs. 21 and 22, Plate IV, illustrate very beautifully the deflection when fast electrified particles like beta rays pass through a uniform magnetic field.

As we have already pointed out, the direction of the magnetic deflection of alpha rays shows that they are positively charged particles. Measurement of the amount of deflection of a ray coupled with a direct determination of its charge shows that it is a particle four times heavier than a hydrogen atom, and that it carries a charge of two positive units. It is therefore essentially an atom of atomic weight 4 and atomic number 2. The speeds of all alpha rays are not the same, but they may reach one-tenth the velocity of light, or 18,000 miles a second. They are much less penetrating than beta rays, being stopped entirely by a sheet of paper or by a few centimetres of air.

Cloud photographs of alpha ray tracks make a

striking contrast with those of beta rays or of electrons in general. Compare Fig. 15, Plate II, a photograph showing the paths of two single alpha particles, with either Fig. 14, Plate II, or Fig. 22, Plate IV. It will be seen that in alpha ray tracks no isolated dots representing droplets are visible, but rather an unbroken continuous streak of light. This arises from the fact that the ions created during the flight of the alpha ray are so numerous that the little drops cannot be separated. In the left hand track of Fig. 15, Plate II, it will be noted that the path turns through a small angle to the right, and then just before the end of the track, a second and much sharper turn to the left. These sudden turnings are evidence of the near approach of the alpha particles to the nucleus of an atom. Ordinarily this heavy particle ploughs along without being deflected out of its path even when passing right through an atom. Occasionally, however, the particle in its passage through the atom passes so near the nucleus that its direction is altered as shown in the photograph. The study of such deflections (of what is called *scattering*) when alpha rays strike a thin sheet of gold led to estimates of the size of the nucleus, and to the picture of the atom we have given on page 30. (See also, Fig. 17, Plate III.)

Fig. 16, Plate III, shows in very realistic fashion the shower of alpha particles leaving a radioactive source. It is impossible to view photographs like these without thinking of atoms as very real particles. Equally convincing evidence of the reality of atoms is provided by the spinthariscope, one of the early radioactive "toys." In this arrangement, a speck of radioactive material is placed near a screen coated with zinc sulphide and, with eyes rested, the screen is viewed through a magnifying glass in a darkened room. Little flashes of light are seen to dance about in irregular fashion, somewhat as if in a patch of the sky the stars kept disappearing in one place and reappearing in another. Each scintillation corresponds to the impact of an alpha particle on the screen. We have called this a toy but, as a matter of fact it was the basis of more than one investigation in which the number of alpha particles leaving a source in a given time was counted, and it was used with success in determining how far both alpha particles and protons travel before they are no longer able to ionize.

Nature's Transmutation

A glance at the atomic weight table at the end of the book will show that the element helium, a rare

gas existing in the air in small quantities, has an atomic weight of 4 and an atomic number of 2. Although the conception of atomic number had not been formulated in the early days of radioactivity, the agreement in mass between an alpha ray and a helium atom suggested that these two particles were essentially the same. Evidence that an alpha particle was indeed just a helium atom robbed of two electrons was soon forthcoming. Helium was found occluded in radioactive ores, and in 1903 Ramsay and Soddy showed that it was present in radium emanation, a gas which, as we shall see presently, is manufactured by radium. Most striking of all was a direct experimental proof made in 1909 by Rutherford and Royds. Alpha rays from a radioactive source enclosed in a vessel were allowed to escape through an extremely thin glass window into a second vessel in which they were collected. By a spectrum test it was shown that helium was present in the second vessel in an amount which gradually increased with the number of alpha particles collected. Here was conclusive proof of the identity of alpha particles and ionized helium atoms. So convinced of the truth of this was one of the workers in the Cavendish laboratory many years ago that he burst into song over the matter and this is part of what he wrote.

A radium atom was dying,
And just ere it burst up for aye,
Corpuscles, which round it were flying,
These last dying words heard it say—
Oh, I am a radium atom,
In pitchblende I first saw the day,
But soon I shall turn into helium:
My energy's wasting away.

(F. H. *in the Post-prandial Proceedings of the Cavendish Society*)

The element radium, then, shoots off atoms of helium. Where do they come from? The answer to that question is bound up with the whole story of the unravelling of the phenomenon of radioactivity and has an important bearing on modern researches in the field of atomic artillery. Largely due to the pioneer work of Rutherford and Soddy, the answer can now be given with confidence. In brief outline it is this. The nuclei of atoms of radioactive elements are differentiated from those of ordinary elements by being unstable. In a radioactive atom, every now and then an explosion occurs, and an alpha or a beta particle is projected out of the nucleus. What is left behind must then be the nucleus of a new atom. This in its turn is generally unstable, and sooner or later explodes, shooting off its projectile and turning into

a third atom. This process goes on until a stable nucleus finally results.

A concrete example will make the matter clearer. Radium, a metallic element, by the emission of alpha rays turns into radium emanation or radon, an element which has the properties of a gas. This is not alchemy, but it is a genuine case of the transmutation of one element into another. Man cannot control the process, but he can and does use it, for in many radium centres there are emanation plants constructed solely for the purpose of collecting this gas manufactured by radium. Radon is collected in this way, because it too is radioactive. When radon atoms explode, they give off alpha rays, and atoms of a solid substance, radium A, are born. The process of disintegration continues and radium A, emitting alpha rays, is followed by a whole series of successive generations—radium B, which changes to radium C by the emission of beta rays; radium C to C′ by the emission of beta and C′ to D by the emission of alpha (or alternately C to C″ by emission of alpha and C″ to D by emission of beta); D to E by emission of beta; E to F by emission of beta; F to G by emission of alpha. There the process stops because radium G is stable, being nothing but common lead. We have omitted gamma rays because they are in-

variably associated with beta rays and, moreover, as already pointed out, they are not electrified particles.

It will be noted that radium emits alpha rays only, not all three types of radiation. But when some radium is enclosed in a tube, disintegration processes are going on all the time and hence there is present in the tube a little of each of the radioactive substances in the whole family. For that reason, when we take an ordinary specimen of radium, all three types of radiation are observed.

By the use of nothing but the most elementary arithmetic, a very simple quantitative test may be applied to the above transformations. In the case of all the births and deaths which change the parent radium into sterile lead, a total of five alpha particles and four beta are emitted. Now, since the atomic weight of an alpha particle is 4, five particles represent 5×4 or 20 units of mass. The mass of a beta particle (an electron) is so small that in comparison we may neglect it, except for very special calculations. Therefore, since the atomic weight of radium is 226, the atomic weight of lead should be 226 — 20 or 206. Mass-spectrograph data show that lead has an isotope of mass 206 in perfect agreement with our calculated value. But long before Aston's work on isotopes, Hönigschmid in Vienna had measured

chemically the atomic weight of lead obtained from pitchblende and the value he obtained was 206.05.

By the use of atomic *numbers*, another numerical test may be applied to radioactive transformations. It will be recalled that for the complete identification of an atom both its mass and the number of unit positive charges on its nucleus or its atomic number are necessary. Since an alpha particle has a charge of 2 positive units, the loss of 5 means a decrease in the total positive charge of 5×2 or 10 units. A beta particle, however, has a unit negative charge, and hence the loss of 4 beta rays means that the total amount of negative electricity in the nucleus is decreased by 4 units. But a loss of 4 negative units leaves 4 positive units unbalanced and so corresponds to a gain of this number of positive units. The net effect, therefore, of the loss of 5 alpha and 4 beta particles is a loss of $10 - 4$ or 6 positive units. Since the atomic number of radium is 88, it follows that the atomic number of lead should be $88 - 6$ or 82, as in fact it is.

There can be no doubt, then, that precious radium ultimately turns into common lead. Nature's transmutations are in the wrong direction. The rare is transformed into the base—a veritable nightmare for the alchemist!

Artificial Transmutation

The discovery of radioactivity greatly extended the artillery equipment of the scientist. In range and in speed, beta rays exceeded anything which could be projected from an electron gun, and alpha rays provided ammunition heavier than any which hitherto had existed. It was little wonder that the big guns were soon put to work and certain substances subjected to an intense bombardment by alpha rays.

The whole story of disintegration had shown that nuclei of radioactive atoms are complex and unstable and strongly suggested the complexity of stable atoms. If this is true, it is possible that a direct hit by a heavy particle like an alpha ray might smash the nucleus of an atom into its constituents. Breaking up the atom in this way must not be confused with releasing some of the electrons surrounding the nucleus. The removal of one or more of these extra-nuclear electrons does not destroy the atom, for subsequently other electrons are attracted by the ion and the atom returns to its normal state. Breaking up the nucleus is a different matter. It means a complete destruction of the atom, and for two reasons it is a very difficult thing to do. In the first place, it may require an enormous amount of energy, and in the second place, the nucleus must be hit "head-on." In

some cases an alpha particle moving at high speed has the necessary amount of energy, but the chance of it making a direct hit is extremely slight. As the nucleus occupies about as much space in an atom as a fly in a cathedral, the vast majority of bombarding alpha particles pass right through the atom leaving it intact, except for the occasional removal of an outside electron.

Sometimes the approach to the nucleus is so near that the alpha ray is deflected to one side and, at the same time, the struck atom—or, more accurately, its nucleus—has energy communicated to it and moves off to the other side. Fig. 17, Plate III, a cloud-track photograph taken when alpha rays were bombarding ordinary helium, provides an excellent example of this. It will be noted that the tracks are straight lines for all but one of the particles. As the photograph clearly shows, the single exception is marked by a forked track, one prong of which corresponds to the deflected path of the original alpha ray, the other to the path of the struck helium nucleus.

Occasionally the bombarding particle strikes head-on, and the struck nucleus, if light as hydrogen, is shot ahead with high speed. In one of the early experiments, for example, alpha rays bombarded

hydrogen, and the protons which had been hit in this way, were observed to cause scintillations on a screen placed far beyond the range of the original alpha particle.

And sometimes the alpha particle enters right into the bombarded nucleus forming an unstable atom which disintegrates. A transmutation is then the result. In 1919 Rutherford bombarded the gas nitrogen with alpha rays and obtained hydrogen because of such a process. For the first time man had formed one element out of another. The amount of hydrogen manufactured, it is true, was too small to be detected by chemical means, but the most rigid tests showed that the effect was none the less real. There was no doubt about it. Protons or hydrogen nuclei were knocked out of nitrogen nuclei. The process of obtaining hydrogen in this way was not very economical, for a million alpha particles had to be fired to give one direct hit, and so to form one atom of hydrogen. But it was not the quantity of hydrogen evolved that mattered, rather the fact that a direct proof had been given that protons existed in the nuclei of nitrogen atoms. Within a few years it was shown that protons could be knocked out of many other atoms as well, and the view that all nuclei are comprised of electrons and protons became widely

held. This, however, is a question we are not yet ready to discuss in detail. Before we can do so, we must learn a good deal more about atomic projectiles.

In a subsequent chapter we shall show that when an alpha particle interacts with a nitrogen nucleus with the emission of a proton, an oxygen atom is also formed. A cloud-track photograph of this transformation, taken a number of years after Rutherford's classic experiment, is shown in Fig. 18, Plate III. In this photograph note the fork at the end of one of the alpha ray tracks. The long, thin "streak" forming one arm of the fork, corresponds to the proton path, the much shorter and a little irregular second arm to the track of the oxygen atom.

CHAPTER VI

MASS WITHOUT MATTER

Photons

In the preceding chapter gamma rays were dismissed with the brief statement that they were similar in nature to x-rays. The dismissal, however, was only temporary, for gamma rays must be included in the list of high-speed particles. To appreciate their significance in atomic artillery, it is necessary to understand something about light.

In Newton's time there were two theories regarding the nature of light. According to one a luminous body emits invisible but material particles which cause the sensation of light when they strike the eye. According to the other, light is a wave phenomenon, the waves being the result of vibrations in the luminous source. In the nineteenth century it was shown that light could be added to light and produce darkness, a fact which, with many others, can be explained only by a wave theory. Throughout that century experimental evidence in favour of this

theory accumulated to such an extent that in 1889 Hertz, a famous German scientist, made the statement that "from the point of view of human beings, the wave theory is a certainty." Hertz was no doubt strongly influenced by the evidence in favour of the particular form of wave theory known as the electromagnetic theory of light. Maxwell, the founder of this theory, showed theoretically that light waves must be of the same nature as electrical waves, and subsequent experimental work by Hertz and others brilliantly confirmed this prediction. We now know that light rays, infra-red rays, ultra-violet rays, x-rays, gamma rays, electrical waves, radio waves are all electromagnetic radiations which travel through space at the enormous speed of 186,000 miles a second. Differences in their properties arise solely from differences in the lengths of the waves.

Few readers need to be told that light represents energy. When the sun's rays are absorbed by matter, heat is developed; and heat may be used to turn water into steam and to run an engine. Indeed, ultimately all our terrestrial activities depend on the energy received by radiation from the sun. Not all of this radiant energy, however, comes in the form of visible light. A portion is represented by waves both longer and shorter than those of ordinary light.

But whether long or short, all electromagnetic waves carry energy which may be revealed by suitable means of absorption.

If light waves are electrical in nature, they must have an electrical source. What is it? At once there comes to mind the picture which has been given of the Rutherford atom. An electron rapidly whirling about a nucleus seems just what is wanted as a generator of light waves. Moreover, according to all the laws of mechanics and of electrodynamics of the nineteenth century, rotating electrons *should* send out electrical waves. But when physicists set out to deduce from these electronic motions in the atom observed laws of light, they could make no headway. Many of the simplest facts defied explanation. For example, according to these dynamical laws an electron rapidly rotating about a nucleus as in the hydrogen atom, would radiate a continuous spectrum, that is, a wide unbroken band of colour. Actually the light emitted by radiating hydrogen atoms consists of a few narrow isolated portions of such a spectrum. Similar difficulties were met with at every turn. Nineteenth-century dynamics applied to the Rutherford atom completely failed to explain observed facts of radiation.

For a satisfactory explanation a totally new con-

ception was necessary. This was provided by Max Planck, an outstanding German physicist, who, in 1900, solved a problem in radiation which for many years had baffled the keenest minds the world over. According to Planck, radiant energy is not emitted continuously as nineteenth-century dynamics required —like water out of a hose,—but discontinuously, in jerks as it were, in little bundles called *quanta,* more like bullets out of a machine-gun. Although this idea of Planck's was a flat contradiction of certain nineteenth-century beliefs, his work did not, at the outset, startle the scientific world. Possibly one reason was the fact that the intermittency was at first confined to processes of emission and of absorption of light. Out beyond the source of radiation, the energy was thought to spread out continuously and uniformly, just like the waves which spread out on the surface of a pond from the place where a stone has struck the water. It soon became evident, however, and here the pioneer in new ideas was Einstein, that even in free space it is often necessary to think of light as concentrated in little bundles which are now called *photons.* If we compare a source of light or of any electromagnetic radiation to a machine-gun, the photons are the bullets which leave it. A photon, then, is a corpuscle or a particle of radiation; it possesses a

quantum of energy; and it travels through space at the rate of 186,000 miles a second.

This would seem to be a return to Newton's ideas, and in some respects it is. Newton's light corpuscles, however, were particles of matter subject to ordinary laws of mechanics, whereas photons are non-material. They exist only when travelling at 186,000 miles a second. Stop them and they completely disappear. But they are none the less real, and *since they represent a certain amount of energy, they possess mass just as material particles do.* It is difficult to think of light having mass, and it is not easy to show its existence by direct experiment, but that has been done. During total solar eclipses convincing evidence has been obtained that light from stars is deflected a small amount out of its path if the light passes near enough to the sun. The sun attracts a photon in the same way as a material particle.

Photoelectricity

There is plenty of other evidence that the impact of a beam of light on a surface is, in some respects, like a shower of raindrops or a stream of buckshot. One of the most striking illustrations of this is provided by the phenomenon of photoelectricity. When light falls on certain metals, a stream of electrons is

emitted—that is the meaning of photoelectricity. An electric current may be started by a beam of light or it may be stopped if the beam is intercepted. In modern industry this principle has many applications, in all of which the control apparatus is a photoelectric cell, a simple device which acts as a regulator of electric currents in response to variations in the intensity of a beam of light incident on a metal surface.

The fact that electrons are emitted in this way does not in itself prove that a beam of light is like a stream of corpuscles. Indeed the photoelectric emission of electrons was known long before any such conclusion was drawn. But when careful investigation was made of the quantitative laws of photoelectricity, it was found that they could be explained only in terms of a corpuscular theory of light. Experiments showed, for example, that the velocity with which an electron emerges from the metal surface does not depend on the brightness of the light. The total number of electrons emitted does, but whether the light is dazzling or dim, an electron leaves an atom with the same maximum speed. It is pulled out of the atom just as easily when the source of light is a mile away as when it is only a foot. This is a very remarkable fact, for, if applicable to any kind of wave motion, to water

waves, for example, it would mean that a large stone thrown into a lake could upset a small boat on the far shore as readily as one nearby. We know that this is not true of water waves, but the quantum theory tells us that it is possible with radiation, if radiant energy does not spread out like water waves, but rather travels concentrated in corpuscles or photons. On striking an atom, whether it is near, or far from the source, the quantum of energy is "swallowed whole," and communicated to the ejected electron.

A photon is thus easily annihilated by absorption. It has another peculiar property. Its energy—and hence its mass—depends on the kind of light used. In general, the shorter the wave-length of the radiation, the greater the energy or the greater the mass of the photon. A photon of red light has a mass so small that it has to be increased 240,000 times to become as large as the mass of a slowly moving electron. If we change to violet light, which is physically distinguished from red by its somewhat shorter waves, the mass of a photon is a trifle larger, although we must still multiply it by a number as large as 170,000 to obtain the electronic mass. If we consider x-rays, electromagnetic waves some of which are so short that they pass readily through a brick wall, the mass

of a photon becomes very much larger. In the case of the most penetrating x-rays, it may take only four photons to give a mass equal to that of the electron.

Gamma Rays

Gamma rays, as we have previously stated, are electromagnetic waves, similar in their properties to x-rays, but of still shorter wave-lengths. They are so penetrating that they will pass through several inches of lead, and, like alpha and beta rays, they ionize a gas through which they pass. Because of the extreme shortness of their waves, the masses of gamma ray photons are greater than those of x-rays. For the gamma ray with the shortest wave-length, the photon has a mass four times greater than that of an electron, and has as much energy as an electron which has fallen through a potential difference of two million volts. It is not surprising, as we shall see later, that gamma rays have been used with success in bombarding atomic nuclei.

It may seem highly contradictory to state in the same paragraph that gamma rays (like light rays) are both waves and particles, and undoubtedly there are difficulties in explaining how this is possible. It is no solution of the difficulty to say that modern science has shown that particles (like electrons and

atoms) sometimes behave as if they were groups of waves, but this fact may help the reader to realize that a certain duality seems to be of the very essence of things. Both matter and radiation have a sort of Dr. Jekyl and Mr. Hyde existence. Each has both a wave and a particle nature. But this subject, fascinating as it is, does not lie in the direct path of our narrative, and we shall pursue it no further.

In yet another way x-ray and gamma ray photons have shown their individuality and given evidence of a corpuscular nature. When a photon collides with an electron (unattached or loosely tied to an atom), the collision is not unlike that of one billiard ball with another. On impact one ball imparts some of its energy to the other, and the two move off in different directions. By actual experiment it has been shown that, when a photon, moving in the direction marked 1 in Fig. 19, strikes an electron at P, it com-

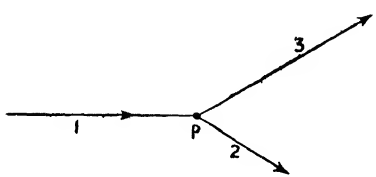


Fig. 19.—A photon moving along the path 1 collides with a free electron P to which it communicates some of its energy. The electron moves off in direction 2, and a photon of reduced energy goes off in direction 3.

municates part of its energy to the electron. The electron then moves off in direction 2, and the photon, with lessened energy, and consequently smaller mass, goes off in direction 3. It is very like the collision of an alpha particle with a helium atom illustrated in Fig. 17, Plate III, although there is an important difference. When the material alpha particle gives up some of its energy, it slows down, retaining its mass (except for the extremely small amount corresponding to the lost energy); but when the non-material photon loses part of its energy, it goes off with reduced mass, but undiminished velocity. Photons, it will be recalled, exist only when travelling at the speed of light.

Measurement of Energy—Electron-volts

Photons may seem somewhat ghost-like, but if they have not material bodies, they are not lacking in energy, and it is the possession of energy that enables projectiles to do work. Since in atomic artillery calculations the exact amount of energy of a projectile must be known, it is necessary to understand just how it is measured. A body possesses energy when it is able to do work, and under no circumstances can work be done unless somewhere there is a supply of energy. An electric motor may make the wheels go around in

a factory, but not unless it is supplied with electrical energy. A dynamo can supply electrical energy, but not unless coils of wire are rotated in a magnetic field by a steam-engine or by water-power. The steam-engine will not run unless supplied with heat by the combustion of fuel, and water will not fall unless it is raised to a height. In the last analysis the sun is responsible for both fuel and the lifting of water from a low to a high level, and is the ultimate source of all our supplies of energy.

There are different units used in measuring the amounts of energy taking part in any transaction. The physicist speaks of so many foot-pounds, or ergs, or electron-volts, and even the householder who has to pay electric bills, may not be unfamiliar with another unit, the kilowatt-hour. Only one or two of these, however, need receive our attention. The foot-pound almost explains itself. When a mass falls to the earth, it acquires energy of motion—kinetic energy it is called—and the farther it falls the greater the energy. If the mass weighs one pound and it falls through a distance of one foot, the energy acquired is said to be one foot-pound. Thus, if a mass of 2,000 pounds falls through a distance of 300 feet, the energy at the end of the fall is 2,000 $\times$ 300 or 600,000 foot-pounds.

In atomic artillery most of the projectiles we have so far encountered are electrified particles, and some of them, such as cathode and positive rays, acquire energy because they are speeded up by an electric field. In such cases the amount of energy acquired depends on the electric charge on the particle and the potential difference through which it has fallen. Since the charge on any particle is always some multiple of that on an electron, *a convenient unit of energy is the amount acquired by an electron in moving through a potential difference of one volt.* This unit is called the *electron-volt.* A cathode ray, for example, moving in a tube with 100,000 volts across its electrodes, acquires a maximum energy of 100,000 electron-volts. A singly-charged positive ion, say of hydrogen, in the same tube would acquire the same number of electron-volts, although because of its much greater mass it would not get up as high a speed as the electron. A doubly-charged positive ion, that is, one which has lost two electrons, in this tube would acquire 200,000 electron-volts.

Although alpha and beta rays possess energy because an atomic explosion shoots them from a radioactive source with high speed, not because of an applied voltage, their energies are frequently expressed in terms of the same unit. Thus an alpha particle

with a speed of a little less than one-twentieth of the velocity of light has four million electron-volts of energy. Alpha particles have been obtained with energies as high as eight million electron-volts, and some very fast beta rays reach nearly the same figure.

To obtain comparable values by the application of high potentials to electrified particles, several million volts are necessary. Since, as we shall see, such high voltages can be obtained and used only with great difficulty, in radioactive materials Nature has provided scientists with the equivalent of elaborate and costly apparatus.

CHAPTER VII

COSMIC RAYS

Nature has been generous in supplying projectiles. We have seen how from mother earth man may extract radioactive materials which, without either powder or power, eject heavy alpha particles, light betas, and fast photons. Since the firing never ceases, the ammunition must be handled with care. It would be disastrous to go about with even a small quantity of radium in one's pocket, for uncontrolled bombardment of one's body with these radiations is dangerous. Radium burns may even be fatal.

There are other kinds of projectiles provided by Nature from which we cannot escape. At all times and in all places, a shower of invisible rays is falling on and passing through our bodies, rays which individually possess energy in amounts far exceeding anything encountered in radioactivity. These rays, originating we know not where, rush in from outer space and are appropriately called *cosmic.*

The discovery of cosmic rays takes us back to the beginning of the twentieth century. At that time a

great deal of attention was being paid to a study of the ionization of air. We have already seen that when alpha and beta rays plough through a gas, their paths are marked by trails of ions. Ionization is, therefore, always present in the neighborhood of a radioactive substance, and, indeed, is one of the most sensitive indications of the presence of such material. For quantitative measurements all that is needed is a device revealing the amount of ionization caused by the substance. One of the simplest of these devices is a gold-leaf electroscope, an instrument which consists essentially of an insulated metal rod R, to which is attached a light metallic strip L, somewhat as shown in Fig. 20. If the rod and leaf are given an

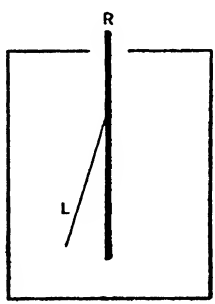


FIG. 20.—Diagram of a simple electroscope. *R* is an insulated metal rod to which is attached a light metal leaf *L*. When the rod is given an electric charge, the leaf is deflected. If ions, either positive or negative, are present in the neighbourhood of the rod, it gradually loses its charge because the ions of opposite sign are attracted to it. The loss of charge and the presence of the ions is made evident by the gradual fall of the leaf.

electric charge, the leaf, because of the repulsion of like charges, is pushed away from the rod an amount which is greater, the greater the charge on the system. If the rod is well insulated, ordinarily the leaf will remain deflected for hours, possibly for days, but if a piece of radioactive substance is placed near the electroscope, the leaf falls quickly, sometimes in less than a second. The explanation is simple. The air is ionized by the radioactive material, and the rod and leaf, if negatively charged, attract positive ions, or if positively charged, negative ions. The charge on the rod and leaf is thus gradually destroyed, and the leaf falls. The greater the amount of ionization, the faster the fall of the leaf.

If radioactive materials are kept away from the electroscope, although no change in the deflection of the leaf may be detected after an hour or more, close observation shows that there is an extremely slow fall. Ultimately the electroscope loses its charge. This can arise from one or both of two causes. The insulation separating the rod from the protecting case may not be perfect, and there may be a small amount of residual ionization in the air at all times. Early investigators examined both these possibilities with great care, and showed that, although the first cause is always operative to some extent, even when allow-

ance is made for it, there is no doubt about the existence of the second. *A few stray ions are always present in the air.*

If there are ions, there must be an ionizing agent. What is it? In answering that question, electroscopes were surrounded with thick layers of lead and of water, they were set up on frozen lakes and on ships in mid-ocean, and it was shown conclusively that at least part of the residual ionization was due to a penetrating radiation coming from outside the apparatus. At first this was thought to be a gamma radiation coming from traces of radioactive materials known to be present in the ground and in the air, but, when in the pre-war years following 1910 observations were extended to the upper atmosphere by the use of balloons, it was soon seen that this theory was not tenable. It was shown, notably, by Hess, an Austrian, and Kohlhörster, a German, that the intensity of the penetrating radiation increased with altitude in a manner which would be impossible if its origin were terrestrial. The higher up the balloons, the more intense the radiation became. Hess concluded that the radiation must come from some source outside the earth and its atmosphere. They are *cosmic* rays.

The establishment of the non-terrestrial origin of these rays does not tell us what they are, nor how they

originate. Fast electrified particles ionize air and may be very penetrating, but the same may be said of photons. To which class do cosmic rays belong? Since moving electrified particles are deflected by a magnetic field and photons are not, it would seem a simple matter to find the answer to this question. Apparently all that is necessary is to pass the rays through a powerful magnetic field and look for a possible deflection. This has been done and beautiful cloud-track photographs (see, for example, Plate IV) have been taken which show trails which look just like beta-ray tracks, and yet, at the present day, many pages in physics journals are filled with discussions concerning the nature of cosmic rays. Nobody doubts that the rays which make the trails are electrified particles. The difficulty is to distinguish between the original or primary cosmic rays and secondary rays caused by the impact of primaries with matter. Since a photon may cause the emission of an electron on being absorbed by an atom, the charged particle may be a secondary electron of this kind, and the original cosmic ray a photon of very high frequency. Or again the particle whose trail is observed may be a secondary electron caused by the impact of a primary uncharged particle. Altogether there are several ways in which the observed particle may have originated.

For ten years or more, numerous investigations have been carried out to determine the ultimate nature of these rays. In the United States, massed attacks on the problem have been made by two large groups of scientists, one under the leadership of Millikan, the other under that of A. H. Compton—both Nobel prize-winners—and in Europe outstanding physicists have continued the pioneer work of Hess and Kohlhörster. Observations have been made on instruments sent up in pilot balloons as high as seventeen or eighteen miles, and the radiation has been detected and measured nearly a third of a mile below the surface of water. Readings have been taken in high-flying airplanes, and in the gondolas which have invaded the stratosphere. Scientists have travelled to all parts of the globe, longitudinally from New Zealand to South America, latitudinally from Northern Canada to the equator. One party alone has had one hundred stations distributed all over the earth. Valuable information has been obtained and strong evidence that a large part of the original rays consists of electrified particles, but as yet complete agreement regarding their origin has not been reached. Let us see which has been found out.

Cosmic rays are extremely penetrating, one hundred times more so than the highest frequency gamma

rays. A few feet of lead or several hundred yards of water will not completely stop them. This means that an individual ray must possess an enormous amount of energy, and actual estimates show that values exceeding 10,000 million electron-volts may be reached. A photon possessing this amount of energy would correspond to a wave-length far shorter than any encountered in gamma rays.

There is no favored direction in space for cosmic rays.* They "come from out of the everywhere into here," with an intensity which for the more penetrating rays at any given place is independent of the hour of the day or the season of the year. If, however, you move about in the surface of the earth, the intensity of the rays does not remain constant. At sea level it is approximately fifteen per cent less at the equator than near the north pole, and at high altitudes, in latitudes above 40° or 50°, it may be several times greater than at the equator.

This dependence on latitude is a very important point because it is just what is to be expected if the rays are electrified particles. The reason is that particles moving through our atmosphere must pass

* A. H. Compton recently (Dec. 1936) reports that "a directional asymmetry of cosmic rays ascribable to the motion of the earth with the rotation of the galaxy seems to be established by sidereal time variations recently reported . . ."

through the earth's magnetic field, and as we have already seen more than once, electrified particles are deflected out of their paths by such a field. Simple laws of physics show that, when the particles are approaching the earth, they should be deflected away from the equator. The observed dependence on latitude is, therefore, convincing evidence that at least a portion of the rays are electrified particles. As we have already indicated, the objection may be raised that the particles reaching the earth are secondaries which have originated in the upper atmosphere as a result of the absorption of primary cosmic rays. This objection cannot be lightly passed over, but a popular book is not the place to give in detail the various arguments for and against it. Suffice it to say that nobody doubts the existence of an extremely penetrating shower of electrified particles on the surface of the earth, and that even the protagonists of primary particles rather than photons do not hesitate to admit that in the journey across the atmosphere photons may play an important part. An original energetic electron, for example, may strike an atom and cause the emission of a photon, which in its turn is later absorbed by another atom with the emission of a fast electron, and so on. The last word has not been written about the nature of cosmic rays, and we may

safely leave the discussion to the experts. Continued observation and experiment will finally settle the question. There is no doubt about the main fact. Whether primary or secondary, particles many times more energetic than anything which can be produced in the laboratory, or obtained from radium, are incessantly bombarding the earth and all things on it. They pass through our bodies and do us no apparent injury, but when such particles collide with the nuclei of atoms there is a different story to tell.

The Positron

Much information about the effects of such collisions has been obtained by the use of cloud-track photographs. By means of a device which greatly multiplies the ionization produced by a cosmic ray and is placed on either side of the chamber in which these photographs are taken, electrical circuits may be arranged so that a cloud-track photograph is taken immediately after a cosmic ray has passed through. Since the chamber is placed in a powerful magnetic field, any rays which traverse it, if electrified particles and if not moving too quickly, are deflected with resulting *curved* tracks. Hundreds of such photographs have been taken, notably by Anderson in America, and by Blackett and co-workers in England,

and remarkable results obtained. Let us look at some of them.

Sometimes a single straight and so, undeflected, trail is obtained, like one of these appearing in Fig. 21, Plate IV. From the appearance of the dots representing the ions, it is concluded that this trail corresponds to an electrified particle of electronic mass moving too quickly to be deflected. On this same photograph, which was taken with a lead plate placed across the cloud-chamber, note the beautiful example of a much slower electrified particle sweeping out the circular path. This particle was liberated from the metal plate as a result of the impact of an incident electron, whose path is the slightly curved track on the upper left of the photograph. Not infrequently, however, the photographs are more complex, showing several curved tracks. A simple example of this is given in Fig. 22, Plate IV, in which there are tracks *curved in opposite directions*, but all apparently radiating from a centre at the edge or just outside the chamber.

The curvature in opposite directions of particles apparently coming from the same source strongly suggests that there are two kinds, one with a positive charge, the other with a negative. The only known negatively charged particle is an electron, but we have

become familiar with two positive particles, alpha rays and protons. The assumption that the path curved in one direction is caused by an electron is greatly strengthened by the appearance of the trail, because the little dots representing ions look exactly the same as those obtained with beta rays and fast electrons. Moreover, estimates of the energy of such particles, based on the measured curvature of their tracks (and the assumption that they are electrons), lead to values in agreement with observations of their penetrating powers. We get into difficulties, however, when we try to ascribe the trail of opposite curvature to either an alpha particle or a proton. This trail also looks exactly like that of an electron, and not at all like the heavy continuous line representing the trail of an alpha particle or of a proton. (See, again, Fig. 15, Plate II). If, disregarding this similarity to the path of an electron, the particle is assumed to be either an alpha ray or a proton and its energy is calculated making use of the amount of curvature, values are obtained far too small to account for the observed penetrating power. All the evidence, therefore, indicates that the trail is caused by a positively charged particle of mass comparable with that of an electron. When cosmic ray cloud-track photographs were first taken, no such particle

was known to exist, but this was the conclusion to which Anderson, and not long afterwards Blackett, were driven.

So important is the discovery of a new fundamental particle that Anderson did not announce his results until he had examined another possible explanation of the track with curvature opposite to that of the electron. It was conceivable that it might be caused by an electron travelling in the opposite direction, because negative electricity moving up has the same effect as positive moving down. It was not at all probable that electrons would be moving towards as well as away from a centre, but the bare possibility that this might be the case had to be examined. For a conclusive proof that the particle was positive, its direction had to be known with certainty. This Anderson did by a very simple experiment. A lead plate was placed across the cloud-track chamber so that the cosmic rays had to pass through it. In going through the plate a ray is slowed down; because of its reduced speed it is more readily bent by the magnetic field, and hence its path is more curved. The direction of the ray is, therefore, towards the side where its path is the more curved. In this way Anderson showed that his assumption of positive particles was correct, and proved beyond all question the

existence of the *positron.* The counterpart to the electron had been found, a particle with comparable mass, but with a positive instead of a negative charge.

We have already called attention to the group of tracks, apparently radiating from a centre, clearly visible in Fig. 22, Plate IV. These showers, many of which are far more complicated than the one shown in this figure, were investigated with great care, and it was shown that unquestionably many of them radiate from a small centre in the walls or the roof of the chamber, or in the surrounding material. There is every indication that they arise from the impact of a cosmic ray with the nucleus of an atom. A particle or a photon of high energy strikes a nucleus and a shower of high energy electrons and positrons is ejected. It is one of the most striking examples of bombardment in atomic artillery, but it is not easy to be sure of the correct interpretation of the result. Were the electrons and the protons originally in the nucleus, or were they created as a result of energy exchanges in the act of collision? The first suggestion seems the most natural, but the evidence is more in favour of the second, which is another example of Einstein's law of the equivalence of mass and energy. *Particles may be born as well as annihilated.* The problem of the origin of the shower is tied up with

the whole question of the structure of the nucleus, and is one of the many factors which must be considered in the solution of this problem.

After the discovery of the positron it was soon shown that this type of particle could be obtained without resorting to cosmic rays. A gamma ray, for example, in collision with an atom of a light element sometimes gives rise to both a positron and an electron. It is not without significance, also, that shortly before the discovery of the positron, Dirac, an outstanding British mathematical physicist, had been working with a theory which needed for its completion the existence of just such a particle. Once again the prediction of theory is confirmed by experiment.

CHAPTER VIII

BRINGING UP THE BIG GUNS

In the chapter on radioactivity it was pointed out that in 1919 Lord Rutherford obtained protons by bombarding nitrogen with alpha particles. The alpha particle struck the nucleus of a nitrogen atom "head-on," an interaction took place, the nucleus of a hydrogen atom was emitted, and as we shall see later, an oxygen atom was formed. This classic experiment of Rutherford, and similar ones which followed, showed several things. (1) A non-radioactive element by bombardment can be transmuted artificially into a different kind; (2) the nuclei of the atoms of so-called stable elements are complex in structure; and (3) a proton is one of the constituents which go to make up a nucleus. An examination of the structure of a nucleus then became a major problem in physics. In recent years so important has this work become that to-day one can scarcely pick up any issue of any physics journal in any language without finding one or more accounts of investigations relating to nuclear structure.

In many of these researches the method is, in principle, simple and straightforward. Shoot fast particles at a substance, and examine the fragments arising from the bull's-eye shots or the direct hits on the nuclei. For successful firing, there should be as many direct hits as possible, and the bombarding particles should possess high energy values. Because of the small fraction of an atom occupied by the nucleus, the probability of a head-on collision is small—it was only about one in a million in Rutherford's experiment—and the only way of increasing the number of hits is to increase the total number of bombarding particles. With radioactive substances the supply is limited and, moreover, alpha particles are the only heavy kind available. It is quite possible that other particles of atomic size might be even more effective in bringing about nuclear disintegration. Indeed, theoretical considerations suggest that protons should penetrate the nucleus more readily than alpha particles.

Scientists, therefore, in planning a massed attack on the nucleus, have sought to develop other means of shooting particles of atomic size at high speeds. One obvious method of doing so is to operate discharge tubes of the positive ray type (described on page 41) at high voltages. To obtain speeds com-

parable with those of alpha rays by the direct application of high potential differences, a million volts and more are necessary. The development and control of such high voltages is a problem in itself, and the greatest care must be exercised in working with them. If conductors at very high potentials are not well insulated and made free from sharp edges, long sparks will jump to the wall or ceiling or floor of the room in which they are housed.

It is not our purpose to describe in detail the devices which have been used in artificially obtaining high speed ions, but some of them are not without interest to the general reader and merit a brief description. First of all, there is the attempt made by two Germans, Brasch and Lange, and possibly others, to harness lightning. A cable nearly half a mile long was suspended between two mountain peaks in a region in Italy where thunderstorms are prevalent, and voltages as high as fifteen million were obtained. This method had the advantage of being inexpensive, but it is too restricted and uncertain to come into general use. Thunderstorms are not to be had for the asking, and they are not without their dangers.

An Electrostatic Generator

A most spectacular direct means of obtaining voltages as high as ten million has been successfully developed in the United States. The principles embodied in the apparatus are essentially those utilized in the electrostatic machines with the rotating glass plates which some forty years ago were not infrequently to be seen in doctors' offices—or in physical laboratories. This modern high-voltage machine is largely the result of the initiative of an American Rhodes scholar, Van de Graaff, and is appropriately called the Van de Graaff Electrostatic Generator. In it positive charges are constantly added to a large insulated hollow sphere, and negative charges to a second sphere until the potential difference between them reaches the ten million mark. Some idea of the problem to be faced is given by the very dimensions of the apparatus. The spheres are fifteen feet in diameter and are supported by insulating columns twenty-four feet high and six feet across. To house the machine a large air-ship dock is used, in which the tall columns can be moved about in trucks resting on railway tracks. Inside each pillar an endless silk belt, kept in rotation by a motor, passes around a pulley at the bottom and up through an opening to the inside of the sphere where it rounds another pul-

ey to return on its downward journey. In one pillar he belt on its upward journey has a positive charge—exactly the same kind as on a piece of flannel after being rubbed with sealing wax—and in the other the upward moving belt carries a negative charge—just like that on silk after being rubbed with glass. As the belts on reaching the inside of the spheres give up their charges, a supply of positive electricity is constantly being added to one, and of negative to the other until a potential difference of ten million volts has been reached. This enormous voltage can be applied to a large discharge tube placed between the spheres, and as many as ten thousand million million ons shot down the tube at high speed every second. Since electric charges always go to the outside of a hollow conductor, operators can work with perfect safety inside the spheres. Scientists do not usually work inside their research apparatus, but after all here is nothing extraordinary about that in days when housands of people drive about in horseless carriages.

The Cyclotron or Merry-Go-Round Generator

A very ingenious method of obtaining high speed ons without the use of extremely high voltages has been developed in the United States, largely as a re-

sult of the pioneer work of Lawrence and Livingston. This method consists in giving an ion at regular intervals a succession of low voltage pushes until it acquires the speed equivalent to a high voltage. The same principle is used when a child is swung to great heights in an old-fashioned long-rope swing. To obtain high amplitudes the child must be pushed at regularly timed intervals. Similarly in the *cyclotron* an ion, after moving at a low speed through a small half-circle receives a push which sends it on at greater speed in a larger half-circle; at the end of the second half-circle, receiving another push it goes off moving still more quickly in a still greater half-circle. The process continues, half-circles being executed at greater and greater speeds and with greater and greater radii, until after perhaps a few hundred or more revolutions, the ion is moving so quickly that its energy is a few million electron-volts. In Fig. 23 (a), the curved dotted line represents a few turns of the spiral path of such an ion.

For the satisfactory operation of such a scheme, two things are necessary. (1) The ions must be made to move in half-circles; and (2) the pushes must be properly timed. The first condition is easily realized by the application of a principle which should now be familiar to readers—a moving charged particle is

deflected by a magnetic field through which it passes. Attention has already been directed to the curved cloud-tracks of electrons and positrons shown in Fig. 22, Plate IV, where it will be recalled, the particles were moving in a uniform magnetic field; and in Fig. 21, Plate IV, a beautiful example is given of an electrified particle describing an almost exact semi-circular path. Now it is not difficult for a physicist to show

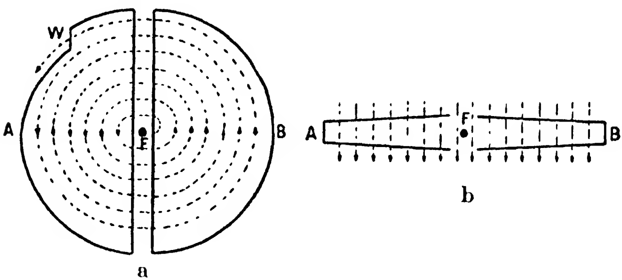


FIG. 23.—*A* and *B* represent the dees of a cyclotron, the dotted arrows in diagram *a* indicating the magnetic field in which the dees lie. By making *A* and *B* alternatively positive and negative, and suitably adjusting both the frequency of the alternations and the strength of the magnetic field, an ion originating at *F* can be made to spiral around and around (many times more than is indicated in diagram *a*) until it emerges through a thin window *W* with very high speed. (Adapted from Physical Review illustration.)

that in such a case, the curved path *is* part of a circle; that the radius of the circle is larger the faster the particle is moving; and that the time the charged particle takes to execute a half-circle is the same whether its speed is large or small. The last fact means simply that the speed for the longer less-curved path

is just enough greater to enable the particle to do the half-circle in exactly the same time as one moving at a slower speed in a more curved path.

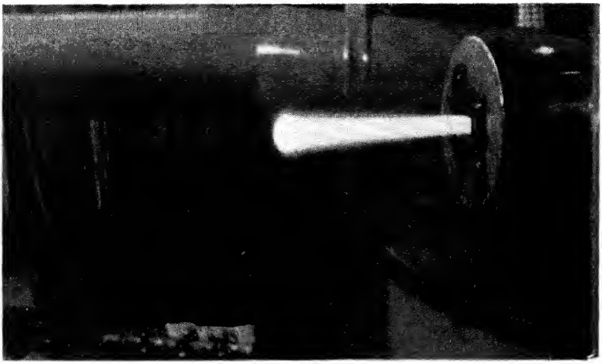
To deflect particles of atomic size strong magnetic fields are necessary and the construction of a sufficiently powerful electromagnet for a good cyclotron is a big job in itself. Here are a few details about the magnet used by Professor Lawrence in the cyclotron illustrated in Fig. 24, Plate V. The pole faces are over two feet in diameter. "The total weight of the magnetic circuit consisting of seven sections of cast steel . . . is about 65 tons." The copper coils carrying the current which magnetizes the iron weigh about 9 tons and are immersed in oil. In the photograph the large drum-like pieces represent the outer casing surrounding these coils.

To realize the second condition, that is, the correct timing of the impulses which make an ion go a little faster every half-circle, use is made of the rapidly alternating voltages which can be maintained between two conductors by means of high-frequency circuits. Circuits of this kind are nowadays in common use, being the type necessary for the generation of radio waves, and details concerning them need not concern us. Suffice it to state that it is not a difficult matter to maintain between the two conductors

marked A and B in Fig. 23 a potential difference of several thousand volts which alternate from A positive and B negative to the reverse, a few million times a second. In the actual instrument A and B are hollow semi-circular boxes frequently called D's or *dees*, somewhat as shown in Fig. 23 b, which lie in the region between the pole pieces of the powerful magnet. In Fig. 24, Plate V, the position of the dees is clearly shown right at the centre of the photograph.

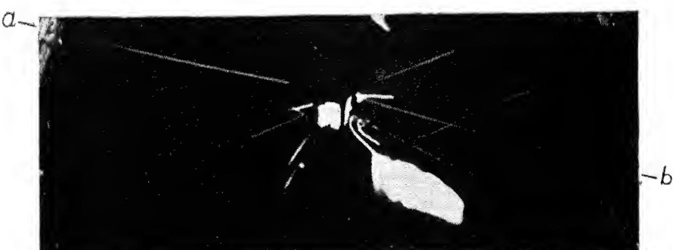
When the machine is in use, the air is exhausted from the boxes, a little gas such as hydrogen is allowed in at low pressure, and ions are created at the centre by some such device as a heated filament. The value of the magnetic field and the frequency of the oscillating electric circuit are so chosen that during the time of a reversal of voltage between A and B the ion to be speeded up moves through exactly half a circle. Whenever, therefore, an ion is pushed from A to B on the right side of the box, it will be pushed from B to A on the left, and so continue on its circular motion in paths which ever widen because of the increase in speed each half revolution. Just before the sides of the box are reached, the ions pass through a window into an observation chamber.

Sometimes the ions emerge through a thin metal window into the surrounding air. When this is the



Courtesy of E. O. Lawrence.

FIG. 25.—A close-up photograph showing the luminescence in air caused by a beam of high energy deuterons emerging from the cyclotron.



Courtesy of P. I. Dee, E. T. S. Walton, and the Royal Society.

FIG. 26.—*a* and *b* mark the paths of two alpha particles, ejected simultaneously in opposite directions when a bombarding deuteron strikes the nucleus of a lithium^6 atom.

case, they strike the molecules of the air and cause them to emit light of a lavender colour. The path of the ionic beam is then marked by a column of light extending for some distance from the window. This is beautifully shown in Fig. 25, Plate VI, a photograph taken by Professor Lawrence using deuterons (nuclei of heavy hydrogen) possessing some five or six million electron-volts of energy.

If a single push is given by 10,000 volts and an ion makes 200 complete revolutions, it has received 400 pushes or the equivalent of 10,000 $\times$ 400, or 4,000,000 volts. Actually protons and deuterons with energy values of six million volts or more have been obtained in this way, and serious consideration has been given to the possibility of obtaining twenty-five million. In a later chapter some of the results of bombardment with these high speed ions will be given.

There is no doubt, therefore, about the ability of the scientist to obtain artificially a copious supply of high energy projectiles of atomic masses. The machines have been constructed, they work satisfactorily, and they are being put to use in nuclear bombardment. But some of the machines are not without their drawbacks. The cost of a cyclotron is prohibitive for the ordinary laboratory and the construction of both it and an electrostatic generator is an engineering

problem on a large scale. Moreover, investigations with such tools require the services of a group of trained men, and it is only in a few centres that such work can be carried out. It is a big step from Rutherford's pioneer transmutation experiments which can be done with simple equipment by a single observer. The nucleus, however, resists attack with great tenacity, and every means must be used to smash it. If the core of a helium atom contains four protons and our explanation (on page 57) of the lost mass is correct, nearly thirty million electron-volts of energy are necessary to break up the helium nucleus into its constituent protons. This has never been done. It is little wonder that scientists are leaving no channel unexplored for the development of copious supplies of energetic particles for nuclear bombardment. In the next chapter we shall examine a little more closely some of the results which already have been obtained.

CHAPTER IX

MODERN ALCHEMY

In the series of transformations experiments initiated by Rutherford in 1919 the bombarding particles were alpha rays emitted by radioactive sources. When nitrogen and other elements were bombarded by these heavy particles, about once in a million times the nucleus of an atom was hit head-on, and a hydrogen atom—or more accurately, its nucleus the proton—was knocked out of the atom. The ejected protons were made evident by scintillations on a screen, and in some cases were detected at a distance of over a foot from the struck atom.

Protons as Bullets

The development of artificial means of obtaining high-speed particles of atomic size led to other types of bombardment experiments. Outstanding among these was the pioneer work of Cockcroft and Walton in England. These experimenters, using protons as their ammunition, bombarded lithium and produced alpha rays (nuclei of helium atoms). Helium was

manufactured by the addition of hydrogen to lithium. In principle the experiment was extremely simple. Fast protons, shot down the tunnel of a positive ray tube, struck a lithium target and scintillations were observed on a zinc sulphide fluorescent screen carefully shielded from the protons. The nature of the scintillations strongly suggested that they were caused by alpha particles, and subsequent experiments with cloud-track photographs proved without question that this was the truth. A proton struck the nucleus of a lithium atom head-on, and alpha particles were emitted. Indeed, the cloud-track photographs (see Fig. 26, Plate VI) showed that *two* alpha rays are emitted for each struck lithium atom, and this is exactly what should occur. A little very simple arithmetic will make the matter clear, and at the same time serve as an introduction for a numerical test which must be applied to all transmutation experiments. In this particular case the test is that

$$7 + 1 = 4 + 4.$$

But let us see exactly what the test means. If for the present we consider only whole numbers for atomic masses (later we shall discuss the significance of the departure from exact whole numbers), a proton has an atomic mass of 1, an alpha particle of 4, and

lithium has two isotopes of masses 6 and 7. If, now, a proton gets right into the nucleus of an atom of lithium 7 and we neglect the small mass change due to energy transformations (a question which will be considered in due course) the total mass number of the new nucleus must be 7 + 1 or 8. But this is exactly twice 4, the atomic mass of a helium atom or an alpha particle. If, therefore, the new nucleus is unstable and immediately after its formation breaks up into two alpha particles, the arithmetical test is in perfect agreement with the supposition.

By indicating the mass number of an atom by a figure placed at the *upper right* side of the name of the element—as lithium^7—we can, in a kind of shorthand, write down the story of what happens as a result of a bombardment. Here it is for the proton bombardment of lithium^7.

$$\text{lithium}^7 + \text{proton}^1 = \text{alpha}^4 + \text{alpha}^4.$$

The scientist, using the symbols Li for lithium, H for hydrogen, and He for helium, still further shortens this to read

$$Li^7 + H^1 = He^4 + He^4.$$

If you do not like using such symbols, it need not prevent you continuing the story of atomic artillery.

One other example of a transmutation brought about by proton bombardment satisfies the test $23 + 1 = 20 + 4$. It is

$$\text{sodium}^{23} + \text{proton}^{1} = \text{neon}^{20} + \text{alpha}^{4},$$

which means that the nucleus of a sodium atom, on interacting with a proton gives rise to the elements neon and helium. Since the symbol Na (natrium) stands for sodium and Ne for neon, these who like the chemical notation will see that the story of this transformation may also be written,

$$Na^{23} + H^{1} = Ne^{20} + He^{4}.$$

A careful examination of the emission of alpha particles brought about by shooting protons showed that extremely high voltages are not always necessary. Cockcroft and Walton, by the use of electrical transformers and other devices, had available over 700,000 volts, but they were able to bring about the above transmutation using only 150,000 volts. Other workers have successfully disintegrated nuclei with 25,000 volt protons. This result is significant because it is in agreement with the predictions of modern theoretical physics that there is a certain probability of low-speed ions penetrating a nucleus. Although the probability for these is not as great as for high speed particles, it has a definite value. For example,

in one investigation it was shown that for 250,000 volt protons there was 1 successful hit in 1,000,000,000 shots, but for 500,000 volt protons there were 10 successful hits in the same number of shots. Low speed particles may therefore be used with great success if there are enough of them, and any device which increases the total number of bombarding particles, even if the speed is not high, may be extremely valuable in bringing about nuclear transformations. That is one reason why artificial means of producing bombarding particles may be of greater use than radioactive sources. Single artificial devices may be and have been constructed with an output of particles which exceeds that from the total amount of available radioactive substances in the world.

Although a heavy barrage of comparatively low voltage particles is thus of great value in nuclear bombardment, it must not be thought that the five million volt machines should be scrapped. Far from it. The secrets of nuclei are just beginning to be revealed, and no stone must be left unturned which may possibly yield information. All nuclei will not be so readily transmuted as those of lithium, and before their defences are demolished, the highest available voltage may be necessary. Nature gives her highest rewards to those who seek most diligently.

Deuterons as Bullets

In a preceding chapter it was explained that hydrogen has two isotopes, the common variety of mass number 1, and a heavy kind of mass 2, which differs from the light kind to such an extent that it is given the special name deuterium. As soon as deuterium was available, it was inevitable that nuclei of its atoms—*deuterons* they are called—should be used as bombarding particles. A lithium target, for example, was struck by fast deuterons, and the result of the bombardment carefully examined. More than one reaction was found to take place. Sometimes two alpha particles were emitted from each atom of lithium, just as in the proton bombardment of lithium^7. With deuterons, however, it was the lithium^6 atom which was penetrated, with the transformation

$$\text{lithium}^6 + \text{deuteron}^2 = \text{alpha}^4 + \text{alpha}^4\text{, or,}$$

using H^2 as the symbol for deuterium (sometimes D is used),

$$Li^6 + H^2 = He^4 + He^4.$$

The cloud-track photograph in Fig. 26, Plate VI, shows very clearly the trails of two alpha particles ejected in opposite directions as a result of this transformation.

Sometimes protons were emitted when lithium was bombarded in this way. In one investigation recently reported small quantities of the two isotopes of lithium were isolated and the effect of bombarding each separately was examined. With lithium^6 a strong proton emission was observed. This result, besides showing that a deuteron may interact with a lithium^6 atom in more than one way, is interesting because it is a good illustration of the fact that 7 + 1 just as well as 4 + 4 is equal to 6 + 2. The story of this second type of interaction in our shorthand language is

$$\text{lithium}^6 + \text{deuteron}^2 = \text{lithium}^7 + \text{proton}^1\text{, or}$$

$$Li^6 + H^2 = Li^7 + H^1.$$

An atom of heavy hydrogen coalesces with one kind of lithium atom and as a result of the union an atom of ordinary hydrogen and one of the other kind of lithium are born.

When deuterons bombard atoms of deuterium, there is evidence that three isotopes of hydrogen may be involved in the following transaction, involving the numerical test 2 + 2 = 3 + 1.

$$\text{deuterium}^2 + \text{deuterium}^2 = \text{hydrogen}^3 + \text{hydrogen}^1,$$

or

$$H^2 + H^2 = H^3 + H^1.$$

If this were the only evidence of the existence of a hydrogen isotope of mass number 3, one might be skeptical about accepting the truth of this transformation. It has been proved in other ways, however, that this isotope of hydrogen does exist, although only in extremely small quantities.

The Charge Test

It is not always easy to decide with certainty the correct interpretation of a nuclear bombardment experiment, and a much more exact test than the simple numerical one we have been using must be applied. This question we shall examine more carefully when considering the departure of the masses from exact whole numbers and the amounts of energy involved in a transaction. At this stage, however, reference may be made to a deduction made from certain deuteron bombardment experiments by considering not only the nature of the fragments but also the energy with which they are emitted. A number of substances, some of them heavy elements like gold and platinum, on being struck with fast deuterons were found to emit, along with other fragments, protons, and the energy of the ejected or projected protons was measured by observing the maximum distance they travelled from the target—what is technically called the

range of the particles. Frequently more than one group of protons was observed, but in the case of a number of different targets, there was always a group possessing exactly the same amount of energy for each substance. This was taken as evidence that a deuteron, on hitting a target, can sometimes itself be disintegrated. Now there is only one way in which 2 can break up into two whole numbers, namely $1 + 1$. It will not do, however, to jump to the conclusion that the deuteron breaks up into two protons because, while this satisfies the test $2 = 1 + 1$, it does not satisfy another simple, but very important test.

To understand the nature of this second test, it is necessary to recall again that to describe an atom completely two quantities must be known: (1) its mass (which for the present we are considering to be represented by an exact whole number), and (2) the number of unit positive charges on its nucleus, or more briefly, its atomic number. Thus, as explained on page 31, ordinary hydrogen has a mass number 1 and an atomic number 1 also; deuterium has a mass number 2, but being an isotope of hydrogen, it has the same positive charge on its nucleus and so has the same atomic number, 1. A helium atom or an alpha particle has mass number 4, atomic number 2;

and the two isotopes of lithium, mass numbers 6 and 7, have each atomic number 3. Now when nuclei interact or coalesce, since the sum of the positive charges before and after the transaction must remain constant, a second numerical test has to be satisfied. Take, for example, the bombardment of lithium^7 by protons, with the resulting emission of two alpha particles for each lithium atom. As already indicated, the *mass* test is $7 + 1 = 4 + 4$. The *charge* test is

> charge on lithium nucleus + charge on proton
> = charge on alpha particle + charge on alpha particle, or,
> atomic number of lithium + atomic number of hydrogen = atomic number of helium + atomic number of helium.

Numerically, then, the charge test is $3 + 1 = 2 + 2$. If we use chemical symbols and indicate the atomic number by a figure at the *lower left* of the word or symbol, as $_3$lithium or $_3$Li, the complete story of the two tests may be written as

$$_3\mathrm{Li}^7 + {_1\mathrm{H}^1} = {_2\mathrm{He}^4} + {_2\mathrm{He}^4}.$$

But, if you do not like being too symbolic, you can omit this altogether.

Applying the charge test to the breaking up of a deuteron, we see that it cannot give birth to two protons, because before disintegration the total charge is only 1 unit, and two protons would give a total of 2 units. Since experiment proves that protons *are* emitted, we have no alternative but to write

$$\text{deuteron} = \text{proton} + ?, \quad \text{subject to}$$

the mass test, $2 = 1 + 1$

and the charge test, $1 = 1 + 0$

The question mark, therefore, must indicate a product of mass 1 with no charge at all. It is a *neutron.*

Another New Bullet—The Neutron

Although the honour of first recognizing the existence of the neutron must be awarded to Chadwick, working at Cambridge University, Germany and France, as well as England, had a share in the sequence of events which led to its discovery. In Germany, Becker and Bothe, when bombarding certain substances with alpha rays from polonium (a member of the radium family which emits alpha rays without the accompaniment of beta and gamma), observed, particularly from the element beryllium, the emission of a radiation sufficiently penetrating to pass through

tolerably thick sheets of metal. This radiation they considered to be similar in nature to gamma rays.

Following up this work, Joliot and his wife, the daughter of Madame Curie of radium fame, were able with more intense sources of alpha rays, to show (1) that this radiation could penetrate an inch or more of lead; and (2) that when it struck a substance like paraffin wax (which contains a large amount of hydrogen), protons were ejected with great energy. Note the two steps in producing the protons. Alpha rays strike beryllium; beryllium emits this penetrating radiation, supposedly of a gamma ray nature; the radiation strikes the paraffin wax, and protons are ejected.

At this stage Chadwick came on the scene. At Cambridge a particle without charge and with the mass of a proton had been sought for more than once. As far back as 1920 Rutherford in his Bakerian lecture had made reference to the possible existence of a neutron and about the same time Harkins at Chicago had pointed out that the problem of building heavy nuclei from light was much simplified if particles of this nature were available as building bricks. Although attempts to track the neutron down had been unsuccessful, it is not surprising that at the Cavendish laboratory watchful eyes were on the look-out

for any indication of its presence. At any rate Chadwick saw that it was highly probable that at least part of this penetrating radiation from beryllium consisted of neutrons and he set out to prove it. It is not our aim in this book to go into the details of technical discussions, but one or two of the arguments which proved that Chadwick's conjecture was correct are not difficult to understand.

It was clear that the radiation in question knocked protons out of paraffin wax, and it was a simple enough matter to measure the energy of the expelled protons, by examining how far they travelled. When this was done it was seen that it was extremely unlikely that they were knocked out of the wax by a gamma ray. For this to be possible the gamma ray photon would have had to possess some fifty million electron-volts of energy, an amount far in excess of any probable value for such radiation. On the other hand, if the radiation consisted of high speed material particles, each with a mass approximately the same as that of a proton, the behaviour of the emitted protons was exactly what was to be expected. The gamma ray hypothesis (because of the small mass of the photon) was something like assuming that a pellet of buckshot by striking a cannon ball could project it forward, whereas the (neutron) particle

hypothesis made only the reasonable assumption that it was a case of one cannon ball being struck forward by another.

The ease with which the debatable radiation passed through thick layers of lead strongly suggested that the particles, if such they were, were uncharged. When a positively charged particle ploughs through matter there are strong forces of attraction between it and the negatively charged electrons in an atom near which or through which the particle is passing. In consequence, electrons are pulled out of many of the atoms in the path of the particle, the atoms are thereby ionized, and the moving charged particle is gradually slowed up as its energy is thus expended. With an *uncharged* particle, however, no such strong forces exist and the slowing-down process is very much less rapid. Indeed, direct hits on the nuclei of the atoms are mainly responsible for the absorption of such a particle by the medium through which it passes. The slowing-down process of an uncharged particle, therefore, depends on two factors (1) the degree of closeness, and (2) the masses of the nuclei. Actually the absorption is much greater in a light substance than in a heavy, because mass for mass, there are far more nuclei in the light than in the heavy substance. Moreover, the colliding particle,

if of small mass, bounces off a very heavy nucleus with little loss of energy, whereas on collision with a light nucleus, such a particle loses much of its energy. The fact, therefore, that lead is more transparent than light substances to the radiation in question is a strong argument in support of the hypothesis that this radiation from beryllium consists of a stream of neutrons, particles uncharged, whose masses are much less than those of the nuclei of lead atoms. If the mass of a neutron is of the same magnitude as a proton, the neutron in a direct impact against a proton gives up all its energy to the proton, and the marked absorption of neutrons by substances containing hydrogen finds a ready explanation.

Chadwick's conclusion that part of the beryllium radiation was a beam of neutrons was soon confirmed in other ways. When, for example, nitrogen and other substances were bombarded by this radiation and cloud-track photographs taken, it was found that one or more short trails of ions appeared *without any track connecting the spot where the short trails began with the beryllium source.* The explanation was not far to seek. A neutron left a bombarded beryllium atom, ploughed through the cloud-chamber without causing any ionization, struck the nucleus of another atom, such as nitrogen, was captured, and the union

gave birth to ejected ionizing particles whose paths were marked by the short trails on the photograph.

The neutron had come to stay. Transmutation experiments had shown the existence of a new ultimate particle. The physicists' family of particles was growing. To protons, deuterons, electrons, and photons, neutrons had to be added. If a tablet were to be erected in the Cavendish Laboratory in commemoration of the discovery of the neutron, we should place on it the following inscription.

$$\text{beryllium}^9 + \text{alpha}^4 = \text{carbon}^{12} + \text{neutron}^1,$$

or, if space were very restricted, we might shorten this to read

$$_4Be^9 + {}_2He^4 = {}_6C^{12} + {}_0n^1.$$

The mass test, you will note, is $9 + 4 = 12 + 1$; the charge test $4 + 2 = 6 + 0$.

This, however, is not the only way to obtain neutrons. We have already pointed out that there is evidence that deuterons can disintegrate into protons and neutrons. It was not long before it was shown that bombardment of several elements, such as lithium and boron, by high speed deuterons was a very effective way to obtain a supply of neutrons. In this connection high speed accelerators like the cyclotron are invaluable.

Importance of the Neutron

There were two outstanding reasons why the neutron was particularly welcomed by physicists. In the first place, it provided them with a bombarding bullet incomparably more powerful than any of the other projectiles for penetrating the nucleus. Protons, deuterons, and alpha particles, all positively charged, are strongly repelled by the positively charged nucleus of an atom, but neutrons, being without charge, are attracted if they pass very close to the nucleus. The neutron may be moving so quickly that it is not captured easily on near approach to a nucleus, but neutrons can always be slowed down by passage through a light substance. In any case, after the discovery of neutrons, bombarding experiments using these particles as bullets were carried out, and their marked effectiveness in bringing about transmutations demonstrated. Here are two examples.

$$\text{boron}^{10} + \text{neutron}^{1} = \text{lithium}^{7} + \text{alpha}^{4}, \text{ and}$$

$$\text{lithium}^{6} + \text{neutron}^{1} = \text{alpha}^{4} + \text{hydrogen}^{3}.$$

In the biological field, experiments are being carried out in which bombardment by neutrons may prove of great value. Certainly such experiments will lead to the discovery of valuable information.

An excellent illustration of the power of a bombarding neutron to bring about disintegration is found in the fact that, whereas with the fastest alpha particle available, no disintegrations have been obtained of elements whose atomic number is greater than 19, with neutrons elements of high atomic weight (gold for example, with atomic weight 197 and atomic number 79) are readily disintegrated. In the bombardment of heavy elements by neutrons, the work of the Italian physicist Fermi has been outstanding. As such investigations give rise to the production of artificially radioactive substances, further discussion will be postponed until we are dealing with this important matter in another chapter.

The second reason for the welcome accorded the neutron was because it simplified the whole problem of the structure of a nucleus. This, too, is a question to which we must return, but at this point a brief reference to it is not amiss. Before the discovery of the neutron, an alpha particle or helium nucleus, with its mass number 4 and atomic number 2, was considered to be made up of 4 protons and 2 electrons. This satisfies the conditions of mass and charge, but these are equally well satisfied by considering the helium nucleus to be built of 2 protons and 2 neutrons. The fact that sometimes a deuteron

disintegrates into a proton and a neutron, as we have seen and shall see again in the next chapter, suggests that, when we deal with nuclei building, these two particles are of greater importance than electrons. It may be that a neutron is formed by the close union of a proton and an electron, or that a proton is formed by the close union of a neutron and a positron. Such possibilities cannot be lightly cast aside. But the simplest hypothesis is to consider the ultimate building bricks as protons and neutrons. This is of particular value when dealing with isotopes, where we have several atoms whose nuclei all have the same charge, but whose masses differ by 1. This increase in mass, with no increase in charge, follows at once by the addition of a neutron. To this whole question we shall return.

CHAPTER X

PHOTON BOMBARDMENT AND A NEW TEST

In the last chapter we considered several examples of transmutation brought about by nuclear bombardment. We saw that with alpha particles as projectiles, we could knock, sometimes protons, sometimes neutrons, out of atomic targets; and using either protons or deuterons or neutrons we could obtain alpha particles. This liberation of particles takes place because of an interaction between the bombarding bullets and the nuclei which they strike, an interaction so intimate that both parties to the transaction lose their identities and in an act of self-immolation give birth to new atoms. To recall just one example, when the nucleus of a lithium^6 atom coalesces with a deuteron, a lithium^7 nucleus and a proton are the result of the union.

In such transmutations it is not always easy to be sure of the final products. The amounts of the substances involved, except in rare cases, are far too small to be weighed or identified by ordinary chemi-

cal methods and their true nature has to be determined by indirect means.* Ionization tracks in cloud chambers are examined, the maximum distance an ejected particle travels is observed, and the mass and the charge test are applied. But even when these tests are satisfied, there may be uncertainty regarding the final products, as the following examples will show.

When boron is bombarded with deuterons, neutrons are liberated. About that fact there is no doubt, but there is doubt whether the correct interpretation is

boron^{11} + hydrogen^{2} = carbon^{12} + neutron^{1}, or

boron^{11} + hydrogen^{2} = helium^{4} + helium^{4} + helium^{4} + neutron^{1}.

Again, when nitrogen is bombarded with neutrons, each of the following reactions is a possible one.

nitrogen^{14} + neutron^{1} = boron^{11} + helium^{4}

or

nitrogen^{14} + neutron^{1} = carbon^{13} + hydrogen^{2}.

* In at least one case, one of the products of a transmutation reaction has been identified spectroscopically and its volume measured. This has been done by Paneth and co-workers at the Imperial College, London, in connection with the bombardment of boron by neutrons. The transmutation is given by

boron^{10} + neutron^{1} = helium^{4} + lithium^{7}.

Paneth not only identified the helium by the spectroscope, but also measured the volume liberated by a source of neutrons acting for a measured time. Some idea of the delicacy of his measurements is obtained from the fact that he dealt with volumes of the order of one ten-millionth of a cubic centimetre.

In each of these cases the mass and the charge tests are satisfied. To decide between possible alternatives of this kind, another test must be applied. This is much more searching and rigid than either the mass or the charge tests, and before any final answer as to the nature of the products of a nuclear reaction can be given, this test must be satisfied. It is the supreme court of appeal in all doubtful cases. For convenience we shall call it the *energy test.* Let us examine it carefully.

In an earlier chapter it was emphasized that in all energy interchanges there is an exact equivalence between the total amounts before and after the transaction. Although this is a bed-rock principle which has not been overthrown by any of the revolutionary ideas of twentieth-century physics, it can only be applied with exactness when Einstein's law regarding the equivalence of mass and energy is taken into consideration. It will be recalled that, in order to account for the 0.028 unit of lost mass when four protons (or two protons and two neutrons) unite to form a helium nucleus, we made use of this law and stated that the lost mass represented energy released during the union of the four particles.

In symbols we may write Einstein's law very simply by the relation

$$E = m\, c^2,$$

where E stands for the energy equivalent to a mass m, and c stands for the velocity of light. When numbers are used, the value of E corresponding to a mass equal to 1 on the mass scale we have been using throughout the book comes out to be about a thousand million electron-volts (more accurately 933 million electron-volts). If a single hydrogen atom (mass number 1) were annihilated, this then represents approximately the equivalent energy. *If in any nuclear interaction only 0.001, that is, one-thousandth of a mass unit disappears, the corresponding released energy is about a million electron-volts.*

Einstein's law may equally well be written

$$m = \frac{E}{c^2},$$

which is really the same thing. In this form, however, it emphasizes the fact that every amount of energy has an equivalent mass. For example, suppose a bombarding proton emerges from a cyclotron with five million electron-volts of energy. *Due to this energy of motion* the mass of the proton is 0.005 (that is 5 million divided by 933 million) of a unit greater than when it is at rest.

If, therefore, we apply to a nuclear transformation this energy test, which is just the law of conservation of energy in its twentieth-century form, we must write

the total energy including the energy equivalent of all masses is the same before and after the interaction; or *the sum of all masses plus the equivalent masses of any free energies involved is the same before and after the transaction.*

An Example of the Energy Test

When lithium^7 is bombarded by protons, we have seen that alpha rays or helium nuclei are produced. In this transformation a single proton unites with a lithium nucleus and two alpha particles are emitted in opposite direction. From a measurement of the lengths of the tracks of these alpha particles in cloud photographs (see again Fig. 26, Plate VI), the amount of energy which each possessed when it left the scene of its birth, can be accurately evaluated. In one experiment, for example, it was shown that a bombarding proton moving with 300,000 e.v. (electron-volts) of energy caused the emission of the two alpha particles, each of which possessed 8.7 million e.v. The complete story of the transformation therefore, may be written

$$\begin{aligned} &\text{lithium}^7 + \text{hydrogen}^1 + 300{,}000 \text{ e.v.} \\ &= \text{helium}^4 + \text{helium}^4 + 8{,}700{,}000 \text{ e.v.} \\ &+ 8{,}700{,}000 \text{ e.v.} \end{aligned}$$

Now let us do a little arithmetic and work out the total mass equivalent before and after the transformation, *using in our calculations the accurate mass-spectrograph values for mass-numbers of all atoms* concerned.*

Before.

Mass of lithium[7] atom	$= 7.0182$
Mass of bombarding hydrogen[1] atom	$= 1.0081$
Mass equivalent of 300,000 e.v. $= \dfrac{300{,}000}{933{,}000{,}000}$	$= .0003$
Total	8.0266

After.

Mass of 2 helium atoms $= 2 \times 4.0040$	$= 8.0080$
Mass equivalent of 8,700,000 e.v. $= \dfrac{8{,}700{,}000}{933{,}000{,}000}$	$= .0093$
Mass equivalent of 8,700,000 e.v.	$= .0093$
Total	8.0266

Within the errors of measurement the two sides exactly balance. Thus, *the truth of Einstein's law concerning the equivalence of mass and of energy has been verified by direct experiment, and the law of conservation of energy has been shown to hold in nuclear transmutations.*

From the above example it will be realized how

* The objection may be made that the mass of the *nucleus* should be used, not that of an *atom*, which is greater than that of the nucleus by 0.00055, the mass of an electron. This is perfectly true, but no error is introduced into the calculations because the atomic mass is substituted for the nuclear mass on each side of the equation.

much more refined the energy test is than either the mass or the charge test. Indeed, it cannot be applied at all unless masses are known to a high order of accuracy. Recall again that 0.001 of a mass unit corresponds to about one million electron-volts. The importance of exact determinations of masses by the mass-spectrograph, therefore, can scarcely be over-estimated, and Aston, Bainbridge, and other workers are ever seeking to improve the precision of their measurements. In assigning the best final values for atomic masses, results of different observers are compared and, as a very important check, it is seen whether, in any transmutation where the bombarding energy and the energy of the released particles are known, the energy test is satisfied by the substitution of these mass values. Sometimes the agreement is not as perfect as in the above example, and transmutation workers question the accuracy of the mass-spectrograph values. There is then only one thing to be done. The investigations must be repeated with greater care until finally mass values are obtained which satisfy the energy test and agree with mass-spectrograph results. The figures given in Table I, p. 53, have been obtained after checking and re-checking in this way.

Can we get something for nothing?

In the example we have considered in detail from the energy standpoint, it will be noted that a single bombarding proton with 300,000 e.v. or 0.3 million e.v. of energy brings about the release of two alpha particles, each with 8.7 million e.v. In the transaction, therefore, nearly 60 times as much energy has been gained as was lost by the proton. This looks like a very profitable business, but the profit is more apparent than real because for every proton which hit a lithium atom, some ten million were fired without making a direct hit at all. The energy expended in shooting this large number is entirely wasted, and if we take it into consideration, the release of energy by transmutation of this sort is a very inefficient process. Nature guards well her locked-up supplies of energy.

Photon Bombardment

When considering the formation of a helium nucleus by the union of 4 protons (or 2 protons and 2 neutrons), it has more than once been stated that the 0.028 lost unit of mass are represented by an equivalent amount of energy released at the time the four particles were synthesized. In this case the en-

ergy is represented, not by the motion of fast particles, for there are none, but by radiation, that is, by electromagnetic waves of some kind. *A small amount of matter disappeared, and radiant energy was born.*

Earlier in our story we also learned that radiation may *disappear* in order to supply the energy necessary to do work. For example, in the photoelectric effect briefly discussed in Chapter VI a photon of radiation is absorbed by an atom, and an electron is ejected. Radiation supplies the energy necessary to pull the electron out of the atom away from the attraction of the nucleus.

Again, in the same chapter, it was pointed out that sometimes a photon on colliding with a free electron communicates *some* of its energy to the electron, and after the impact bounces off with a smaller amount. In this case *a portion of* the incident radiant energy was turned into the energy of motion of an electron.

It should not be surprising, therefore, to learn that the nucleus of an atom can be disintegrated by the absorption of radiant energy. To bring about such a distintegration, the photon absorbed by the nucleus must possess sufficient energy to enable the constituent parts of the nucleus to be torn apart. For example, to disintegrate a helium nucleus into 2 pro-

tons and 2 neutrons, energy equivalent to at least 0.028 unit of mass would have to be *supplied.* Remembering that 0.001 mass unit corresponds (roughly) to a million electron-volts, you will see that a photon possessing at least 28 million e.v. of energy would be necessary. No such energetic radiation is available, and no one has ever disintegrated a helium nucleus in this way. Its *binding energy,* to use the technical phrase, is much too large.

The binding energy of the constituent parts of an atom of deuterium or heavy hydrogen, however, is only a little greater than 2 million e.v. and radiation with photons possessing energy in excess of that amount is available. A photon of the gamma radiation from thorium C″, a radioactive substance, has an energy of 2.62 million e.v. and has been successfully used in the disintegration of deuterium by Chadwick and Goldhaber. In brief this is the story.

$$\text{hydrogen}^2 + \text{gamma ray} = \text{proton}^1 + \text{neutron}^1.$$

We have already called attention to certain experiments which suggested that a bombarding nucleus of deuterium might on collision break into a proton and a neutron. Here, however, is a direct disintegration into these products brought about by the impact of a photon.

This disintegration satisfies the mass test $2 = 1 + 1$, the charge test $1 = 1$, and when the energy test is applied it provides an excellent means of accurately measuring the mass of the neutron. Let us do a little more simple arithmetic.

Mass of the Neutron

On the one side of the balance sheet, we have to write down the mass of an atom of heavy hydrogen plus the mass equivalent of a gamma-ray photon possessing 2.62 million e.v. of energy. The first mass is accurately known to be 2.0147 units, and the second, according to Einstein's law, is $\frac{2.62}{933}$ or 0.0028 unit. On this side of the sheet, then, we have a total of

$$2.0147 + 0.0028 = 2.0175.$$

On the other side, we have to record the mass of an atom of ordinary hydrogen (whose nucleus is the proton) known to be 1.0081, plus the unknown mass of the neutron, plus the mass equivalent of the energy of motion of these disintegrated particles. By measuring the amount of ionization produced by a proton Chadwick and Goldhaber showed that the energy of motion of both the proton and the neutron

was about ½ million e.v. Since this amount has a mass equivalent of 0.0005 unit, the total to be recorded is 1.0081 + 0.0005 or 1.0086 mass units plus the unknown mass of the neutron.

Since the totals on each side of the balance sheet must be equal, we can write

$$2.0175 = 1.0086 + \text{mass of neutron, or}$$

$$\text{mass of neutron} = 2.0175 - 1.0086 = 1.0089.$$

Summarizing our information before and after the disintegration, we can make our books look properly balanced in this way.

Before

mass of deuterium atom	= 2.0147
equivalent mass of gamma ray photon	= .0028
Total	2.0175

After

mass of hydrogen atom	= 1.0081
equivalent mass of energy of motion	= .0005
mass of neutron	= 1.0089*
Total	2.0175

* 1.0090 is probably a slightly more accurate value.

Birth of an Electron Pair

We see, then, that there is ample evidence that matter may be turned into energy and that radiant

energy may disappear to enable work to be done, or to disintegrate a nucleus into its components. Most striking of all, however, is the disappearance of a gamma ray photon to give birth to the twin children —an electron and a positron. Shortly after the discovery of the positron it was shown that these positively charged particles of electronic mass were produced readily by the passage of short wave-length photons through matter. Thus, when gamma rays of suitable wave-length pass through a layer of lead, positrons are ejected.

This phenomenon has been carefully examined in England, the United States, and the European continent by such skilled observers as Chadwick, Blackett, Anderson, Curie-Joliot, Joliot, and Meitner, and all agree that not infrequently a positron and an electron are simultaneously emitted. The energy test has been applied and there is unmistakable evidence that a photon, when in the region very close to a nucleus, may disappear in whole or in part, to give rise to the electron pair. Here we have an example of the direct conversion of radiant energy into material substance. In this transformation the nucleus plays the part of a silent partner, for it does not enter directly into the transaction. It is rather a kind of controlling agent.

CHAPTER XI

THE FORMATION OF RADIO-ELEMENTS

In Chapter V we showed that a few elements, described as radioactive, have the remarkable property of spontaneously emitting alpha particles or beta particles and gamma rays. It was there pointed out that this emission takes place because the atoms of such elements, or more accurately, their nuclei, are unstable, exploding every now and then with the emission of particles. When a nucleus, as a result of such an explosion, shoots off an alpha particle with its two positive charges, the residue, that is, the nucleus which is left behind, must have an atomic number two *less* than that of the original atom. On the other hand, the emission of a beta particle with its single negative charge, leaves the residual nucleus with an excess of one positive unit, and so gives rise to a new nucleus with atomic number one *greater* than that of the original.

In the course of the series of explosions which takes place in a radioactive family, therefore, the

atomic numbers of the atoms of the successive generations go, sometimes up, sometimes down, and it is not surprising to find the same number occurring more than once. For example, in the radium family, we encounter radium B, radium D, and radium G all with atomic number 82, although their masses are 214, 210 and 206. Of these three isotopes, the first two are unstable or radioactive because they explode into something else, but the third, radium G, does not so disintegrate and is, in fact, a stable atom of lead. This common metal, therefore, provides us with a good example of an element, of atomic number 82, having both unstable or radioactive and stable isotopes, *all occurring in Nature.* In our semi-shorthand notation, we may describe them as

$${}_{82}\text{lead}^{214},\ {}_{82}\text{lead}^{210},\ \text{and}\ {}_{82}\text{lead}^{206},$$

or, in still more symbolic form, since Pb is the chemical symbol for lead,

$${}_{82}\text{Pb}^{214},\ {}_{82}\text{Pb}^{210},\ \text{and}\ {}_{82}\text{Pb}^{206}.$$

Manufacture of Radioactive Isotopes

One of the important results of atomic bombardment was the discovery that it was possible to *manufacture* unstable or radioactive isotopes of elements which, previously, had been considered to have stable

isotopes only. Let us look at one or two examples.

Mme. and M. Joliot working in France found that aluminum foil, which had been bombarded with alpha rays for a few minutes, emitted positrons *after the bombardment had ceased.* The foil could be removed from the source of alpha rays—taken into another room altogether—and when brought near a charged electroscope, caused it to lose its charge just like a natural radioactive body. The aluminum soon lost its acquired radioactivity, decreasing to half-strength in about three minutes, but the effect was unmistakable. Aluminum can be made temporarily radioactive by bombardment with alpha rays. What exactly happens?

An examination of the transmutation products resulting from the bombardment of aluminum with alpha rays, shows that *during the bombardment* sometimes protons are emitted, sometimes neutrons and positrons. The proton emission is readily explained by the transformation

$$_{13}\text{aluminum}^{27} + {_2}\text{helium}^4 = {^{14}}\text{silicon}^{30} + {_1}\text{proton}^1.$$

In this transformation the charge and mass tests are satisfied, and the two products of the transaction are a proton and a stable, known isotope of the element

silicon, whose atomic number is 14. There is nothing new about this.

To account for a neutron emission, the following transmutation must take place.

$${}_{13}\text{aluminum}^{27} + {}_{2}\text{helium}^{4} = {}_{15}\text{phosphorus}^{30} + {}_{0}\text{neutron}^{1}.$$

In this case, the products of the transformation are a neutron and an element which must be phosphorus, because its atomic number is 15. Phosphorus is a well-known element with a stable isotope of mass number 31, but it has no known stable isotope with mass number 30. Mme. and M. Joliot, therefore, concluded that this isotope of phosphorus is unstable or radioactive, emitting positrons when it "explodes." What happens, then, is this. The original bombardment of the aluminum manufactures a certain amount of the 30 isotope of phosphorus. On ceasing fire with the alpha rays, the foil is removed and embedded in it are these new unstable or radioactive atoms. These begin to explode, shooting off positrons.

Since a positron has an almost negligible mass and one unit positive charge, the nucleus left behind after the explosion has practically the same mass as before, but an atomic number one less. In the case of the phosphorus radioactive isotope (atomic number 15), the nucleus is left with 15—1 or 14 positive units,

or it is an atom of atomic number 14. It must therefore be silicon. The radioactive disintegration is then described in our short way by

$$_{15}\text{phosphorus}^{30} = {}_{14}\text{silicon}^{30} + {}_{1}\text{positron}.$$

In about 3 minutes half the unstable phosphorus atoms have turned into silicon.

To distinguish an unstable, radioactive isotope of an element from a stable one, particularly when the elements occur in nature only in its stable forms, the prefix *radio* may conveniently be used. Thus, in the above example, we speak of radio-phosphorus, the radioactive variety of mass number 30 which can be manufactured by bombardment and has a *half-period* of about 3 minutes.

Radio-sodium

After the original discovery of artificial or induced radioactivity it was soon shown that a large number of elements had radioactive isotopes. Protons, deuterons, and neutrons were all found to be effective in manufacturing radio-elements. In Italy Fermi and co-workers bombarded many elements with neutrons and in the United States in the hands of Lawrence and others the cyclotron was put to good use in bombarding experiments. An interesting example is the crea-

tion of radio-sodium by the cyclotron-firing of deuterons against sodium. (Ordinary common salt which is a compound consisting of this element and the gas chlorine may be used instead of pure sodium). In this case the initial transmutation is given by

$$_{11}\text{sodium}^{23} + {}_{1}\text{hydrogen}^{2} = {}_{11}\text{sodium}^{24} + {}_{1}\text{proton}^{1}.$$

It will be noted that the capture by a sodium^{23} atom of a deuteron or nucleus of heavy hydrogen (atomic number 1, mass number 2), with resulting emission of a proton or nucleus of light hydrogen (atomic number 1, mass number 1), leaves the atomic number of the new atom the same as that of the original sodium atom. This new atom, therefore, is still sodium, but sodium with its mass number increased by 1, that is, it is sodium^{24}.

The sodium isotope 24 does not occur in nature, is unstable or radioactive, emitting electrons (or, if you like beta rays) accompanied by gamma rays, when its atoms explode. The story of the exploding atom of radio-sodium is, then, in brief

$$_{11}\text{sodium}^{24} = {}_{12}\text{magnesium}^{24} + \text{beta} + \text{gamma}.$$

As always, the emission of a beta particle or negatively charged electron from a nucleus raises the resultant positive charge by 1 unit, and so in this case,

raises it from 11, the atomic number of sodium, to 12, the atomic number of magnesium. The residual atom is therefore an isotope of mass number 24 of the element magnesium, a stable one occurring in nature.

Radio-sodium^{24} differs from radio-phosphorus in two important respects. (1) Electrons are emitted, not positrons; and (2) since the time it takes for half a given quantity of radio-sodium to explode into stable magnesium is over 15 hours, its average life is very much longer than that of radio-phosphorus.

Recently Lawrence and his co-workers, by the use of very intense beams of deuterons, have produced radio-sodium^{24} in amounts which no longer leave any doubt that artificial radioactive substances may be used to supplement—possibly in time to supplant—Nature's radioactive supplies. This is a very important result because the total amount of radium in the world is limited and it means much to have available ample supplies of radioactive materials. A single day's bombardment of sodium by deuterons with 5 million electron-volts of energy produced an amount of radio-sodium^{24} which had a gamma ray activity the equivalent of an amount of radium worth about $10,000.

An alternate method of producing radio-sodium^{24} consists in bombarding the metal magnesium (atomic

number 12, mass number 24) with neutrons. No detailed explanation should be needed to understand the transmutation in this case. It is

$$_{12}\text{magnesium}^{24} + {_0}\text{neutron}^1 = {_{11}}\text{radio-sodium}^{24} + {_1}\text{proton}^1.$$

A Fascinating Game

We have seen that neutrons, protons, deuterons, helium nuclei, and photons may all be used in bringing about atomic transformations. As there are in existence about 280 known isotopes of all the elements, and as each isotope, theoretically at any rate, can be used as a target for each of these projectiles, a great variety of shooting is available for the nuclear scientist. Firing is in progress at many centres and almost daily progress bulletins announce advances made in this attack on the nucleus. Some idea of the complexity of the operations may be gathered from the following illustrations.

When sulphur (atomic number 16) is bombarded with deuterons, the formation of three different radio-elements has been reported, the first with a half-period of 3 minutes; the second, of 33 minutes; the third of 14 days. This is possible because sulphur has three stable isotopes, with mass numbers 32, 33, and 34, and in an ordinary sample of the element,

all three are present. On bombardment each gives rise to a different radio-element. For the sake of those who like working out things for themselves, we add that the radio-elements formed are $_{15}$radio-phosphorus^{30}, $_{14}$radio-chlorine^{31}, and $_{15}$radio-phosphorus^{32}. It should not take as much time as the solving of a cross-word puzzle, and should be at least as entertaining, to write down the transformation equations.

By way of contrast to this formation of three different radio-elements from the same substance, we call attention to the fact that the same radio-element may be formed in several different ways. One of the best examples is that of radio-aluminum. This radioactive isotope has been manufactured in five different ways—by bombarding aluminum^{27} with both neutrons and deuterons, by bombarding silicon^{28} with neutrons, phosphorus^{31} with neutrons, and magnesium^{25} with alpha particles.

The Manufacture of Gold

The old alchemists diligently sought the philosopher's stone which would help them turn base metals into gold. They did not succeed. The modern alchemist has been more successful, for he has recently created gold out of another substance. But, alas, it is in negligibly small amounts and still sadder to re-

late, the other substance, the element platinum, is more valuable than gold itself. In the transmutation, radio-platinum is an intermediate short-lived product, as will be seen from the following description of the process.

$$_{78}\text{platinum}^{196} + {}_{1}\text{hydrogen}^{2} = {}_{78}\text{radio-platinum}^{197} + {}_{1}\text{proton}^{1}$$

and

$$_{78}\text{radio-platinum}^{197} = {}_{79}\text{gold}^{197} + \text{electron.}$$

There is no danger of the scientist or anyone else trying to patent the process.

CHAPTER XII

THE CONCLUSION OF THE MATTER

Structure of the Nucleus

We have travelled a long way from the indivisible atoms of the mid-nineteenth century. Maxwell's "imperishable foundation stones of the universe" have turned out to be complex structures capable of dividing so that one stone can turn into two, or of uniting to produce stones different from the original. We have seen how the discovery of electrons, those negatively charged particles which, in varying numbers, form the outer structures of all atoms, was followed by convincing evidence that the heavy positively charged core or nucleus of an atom was also complex. In radioactivity we encountered atoms which shot off alpha particles and in the interactions between nuclei brought about by atomic bombardment, we noted that protons as well as neutrons were sometimes ejected from the scene of the interaction. We saw, too, that the study of cosmic rays led to the discovery of the positron, the positive twin of the negative electron, a

particle which was later shown to be emitted by certain artificial radioactive atoms.

The complexity of the atom, therefore, has steadily increased, and an understanding of how the various elementary constituents unite to form different kinds of atoms is of fundamental importance. The solution of such a question is far from complete, but much progress has been made, in no small part due to the results of experiments in atomic artillery. Let us see what picture we can draw to help us visualize some of the newer ideas about atom-building.

To begin with, the Rutherford "solar system" atom is more firmly in the saddle than ever. We still picture an atom as a heavy positively charged core or nucleus surrounded by light negatively charged electrons, in numbers sufficient to neutralize the positive charge on the core. That picture is not questioned. It is with the structure of the nucleus itself that present day investigations, both experimental and theoretical, are concerned. What, for example, are the bricks or sub-units used in the building of a composite nucleus? The answer to that question is the more difficult because of the number of elementary particles at our disposal. We have an embarrassment of riches. Proton, neutron, electron, and positron (see Table II) must certainly be considered, and, al-

TABLE II

Particle	Charge	Mass
electron	—1	0.00055
positron	+1	0.00055
proton	+1	1.0076*
neutron	0	1.0090

* Obtained by subtracting 0.00055 from 1.0081, the mass of a hydrogen 1 atom.

though the alpha particle (mass number 4, atomic number 2), is not quite so elementary, the fact that it is emitted in radioactive explosions and in atomic transformations shows that it plays a special role in atom-building.

Whatever the primary constituents, they must so combine that they give rise to a nucleus with correct nuclear charge and correct mass number. Since the exact masses of all isotopes depart only slightly from whole numbers, it is natural to conclude that a nucleus contains either protons, or neutrons, or perhaps some of each of these particles whose mass number is 1. For example, the mass number 2 of heavy hydrogen is readily accounted for in three different ways: by the union of 2 protons, or 2 neutrons, or 1 proton and 1 neutron. The fact that the sum of the exact masses of 2 protons or of 1 proton and 1 neu-

tron is a little greater than the exact mass of this isotope, need not bother us, because, as we have already pointed out, when particles fuse together, a little matter may disappear, being converted into energy.

To distinguish between these three possible combinations, we must consider the nuclear charge or atomic number, which in the case of heavy hydrogen is 1. For this isotope the elementary particles must be so chosen that the nucleus has a resultant charge of 1 positive unit. We could not have 2 neutrons, for that would give no charge at all; nor 2 protons, for that would give us a charge of 2 positive units. Of these three possibilities, then, there is only one left, the union of one proton and one neutron. Actually, as we have already seen on page 143, the nucleus of a heavy hydrogen atom can be disintegrated into a proton and a neutron by the absorption of a photon. There seems little doubt about the structure of this nucleus. A proton and a neutron in all probability are the sub-units.

There are, however, other ways of accounting for its structure. Two neutrons and a positron (of mass only 0.00055 unit would give mass number 2 and atomic number 1; and so would two protons and an electron, since the negative charge on the electron

would neutralize the positive charge on one of the protons, leaving a net charge of 1 positive unit. Can we rule out these possibilities? As a matter of fact, before the discovery of the neutron and the positron, the only building bricks were protons and electrons and all nuclei were supposed to be built up of these particles. The nucleus of nitrogen^{14} for example, whose atomic number is 7, was considered to be composed of 14 protons and 7 electrons. Although this satisfactorily accounted for the mass and the charge it was not free from difficulties. Without going into technical details, the main point of one of these difficulties can be easily seen by the general reader. The predicted value of a certain quantity called the spin of the nucleus, which can also be determined experimentally, depends on whether the total number of particles in a nucleus is odd or even. Odd gives one result, even another. In the case of this nitrogen nucleus, it will be noted that on the proton-electron theory, there are 14 + 7 or 21 particles—an odd number; but, on the proton-neutron theory, according to which there are 7 protons and 7 neutrons, the total number is even. Since the predicted result based on the even number agrees with the observed facts, and that based on the odd number does not, there is strong evidence in favour of the proton-neutron theory.

The view now generally accepted is that all nuclei are built up of neutrons and protons. A lithium^6 nucleus, with three protons and three neutrons, has the correct mass number 6 and atomic number 3. The addition of a fourth neutron brings the mass number up to 7, leaves the nuclear charge unchanged and so gives us the lithium^7 isotope. No detailed explanation will be necessary to show that an alpha particle must contain 2 protons and 2 neutrons. It all seems very simple and the building up of heavier and heavier nuclei provides good practice in elementary arithmetic. But electrons and positrons cannot be put aside quite as easily as that. It is a well-established experimental fact that radioactive isotopes, either natural or artificial, *do* give off these elemental charged particles. Where do they come from? And surely, it is objected, if a nucleus emit such particles, they must be part of it. The objection is natural, but it does not do to come to a conclusion too quickly. You do not believe that the rabbits which a magician produces really come out of his hat, and it may be that the production of electrons and of positrons can be explained in another way. At any rate the analysis of the whole question of nuclear structure by theoretical physicists has led them "to assume that the electrons observed in beta-disintegration did not pre-exist

in the emitting nucleus." If you ask them where they come from, they have their answer ready. "We suppose that they are formed in the same moment when they are actually emitted." Something out of nothing? No, just an example of energy turning into matter, a transformation in support of which we have already given evidence (see page 146).

If we accept this idea of the manufacture of electrons (and the same applies to positrons) just before they are emitted, an interesting result follows. A proton in a nucleus must turn into a neutron whenever a positron is emitted, and a neutron into a positron when an electron is emitted. It is not difficult to see why this must be so. When an electron is emitted, the total number of positive unit charges increases by 1, but the mass number remains unchanged. There must, therefore, be one more proton (to account for the increase of 1 positive unit), and one less neutron (to keep the total mass unchanged). So we may write

$$\text{neutron} = \text{proton} + \text{electron}.$$

Similarly the ejection of a positron means that when it was being manufactured, a proton turned into a neutron, or that

$$\text{proton} = \text{neutron} + \text{positron}.$$

Structure of the Alpha Particle

It is not our purpose to discuss in detail the nuclear structure of many elements. That would be tedious and, moreover, would not add greatly to the general ideas we have been trying to give the reader. The helium nucleus or alpha particle, however, merits a little attention. The mere fact that it is emitted in many radioactive explosions and nuclear transformations, shows that it is entitled to special consideration. Although it has never been disintegrated into its elementary constituents, the above evidence indicates that it is composed of 2 protons and 2 neutrons. Early in our story we pointed out that if 4 protons united to form an alpha particle, there was a loss of 0.028 unit of mass. Since the mass of a neutron is almost equal to that of a proton (being slightly greater if anything), the union of 2 protons and 2 neutrons makes but little difference in this result, and in no way alters the conclusion previously emphasized, that this "lost" mass represents the release of some 28 million electron-volts of energy when the particles came together.

It follows from this explanation of the lost mass that, in order to break up an alpha particle into its constituents, this large amount of energy would have to be communicated to it, and it is significant that no

such disintegration has ever been accomplished. The alpha particle is a peculiarly stable body, with the so-called "binding energy" of approximately 28 million e.v. By way of contrast, consider the binding energy of a deuteron or heavy hydrogen nucleus. We can find it readily from the following masses.

mass of proton = 1.0076;* mass of neutron = 1.0090; mass of deuteron = 2.0142.*

Before the union of a proton and a neutron, the sum of their masses is 1.0076 + 1.0090 or 2.0166 units. Since *after* the union it is only 2.0142 units, the lost mass is 2.0166 — 2.0142 or .0024 units. This represents an energy release of less than 2.5 million e.v. The binding energy of a deuteron, therefore, is less than 2.5 million e.v., an amount very much less than that of an alpha particle. Since projectiles with energy value exceeding 2.5 million e.v. are available, it is not particularly difficult to disintegrate a deuteron.

Not so with an alpha particle. Once one is formed it "stays put," and it is not surprising to find this particle ejected "whole" from complex radioactive nuclei. It is a stable secondary unit. Further evidence

* These are obtained by subtracting from the masses of the atoms, 0.0005, the mass of one electron.

of this is provided by two additional facts. (1) Nuclei of mass numbers 8, or 2×4 (beryllium), 12, or 3×4 (carbon), and 16, or 4×4 (oxygen) are all more stable than the intermediate isotopes; and (2) "the abundance of atoms of an approximate mass 4m and a charge 2m, where m is a whole number, is very much greater, up to atomic number 30, than all other types of atoms." The more stable a nucleus is, the less it is going to be broken up in any of Nature's catastrophies or explosions, and hence the greater its prevalence.

It will be recalled that in certain bombardment experiments (lithium^7 by protons, for example, as on page 117), alpha particles are formed. This again is evidence of their great stability. There is a law in Nature which states that in all processes the amount of "stored-up" energy tries to become as small as possible. A raised weight tries to get as near as possible to the earth where its energy of position is least; a coiled spring tries to uncoil; and in any re-arrangement of elementary particles, that configuration is most probable which makes the total mass as small as possible. The formation of alpha particles, therefore, which represents a comparatively large decrease in mass, is a likely process.

To sum up, the results of investigations in nuclear

physics strongly suggest that in atom-building the proton and the neutron are the elementary bricks; that the alpha particle, while not elemental, has a unique place because of its great stability; and that electrons and protons are manufactured during the re-arrangement which takes place in nuclear transformations. The problem of the structure of the nucleus, however, is in its infancy, and it will take much work on the part of both theoretical and experimental physicists before it has been solved finally—if, indeed, any fundamental problem in science ever has a final solution.

Is There a Negatron and a Neutrino?

It is by no means established that the particles listed in Table III are the only elementary ones. Is there, for example, a *negatron* or the twin of a proton with a negative rather than a positive charge? Some indirect evidence suggesting the possible existence of such a particle has been given, but it is still no more than a possibility. And is there a *neutrino* (or little neutron), a particle of mass comparable with that of an electron or a positron—or even less—without any charge? The possible existence of such a particle is constantly discussed, because by means of it a certain fact which apparently contradicts the law of conservation of energy can be explained without resorting to

any such contradiction. It is not difficult to understand the general nature of the argument in support of the existence of a neutrino. In some nuclear transformations where beta rays are ejected, there is definite evidence that the energy of the nucleus before the emission differs from the energy after by an *exact* amount. It might reasonably be expected, then, that the emitted beta ray (and associated gamma) would be ejected with an amount of energy exactly equal to the decrease in the amount possessed by the nucleus. Actually, however, beta rays come off with a whole range of energy values, some with amounts far too small to account for the observed energy loss of the nucleus. It has been conjectured, therefore, that, along with the beta ray, a neutrino is emitted with the missing amount of energy. But this particle has proved very elusive, for nobody as yet has been able to capture it.

Of What Use?

A reader of this story of atomic artillery may be forgiven if he asks, what is the use of a knowledge of the structure of the nucleus of an atom? What good will it do anybody? And why build all this elaborate and expensive equipment just to smash atoms? In answering these questions, there are several things which may be said. First of all, it is

doubtful if many of the scientists who spend long and sometimes weary hours in the laboratory trying to find out the secrets of the atom are directly interested in possible beneficial results to mankind. Thinking man has been born with an incurable desire to know the secrets of Nature. He is constantly asking Nature "why" and is not satisfied until he knows the answer. He has an inward urge compelling him to do things just to satisfy his intellectual curiosity. There is joy in creation of any kind and none greater than that which comes to the man who discovers some new fact or principle. The goal of absolute Truth is never reached, but the road thereto, if often rough and uphill, constantly rewards the traveller by the beauty of new views and vistas.

Now while all this is true, it is very remarkable that when man sets out to penetrate Nature's secrets in order to satisfy his intellectual curiosity, he is constantly rewarded in another way. Discoveries which at first apparently had no practical value have led to applications of untold benefit to mankind. Let me illustrate. A good many years ago it was found that when a metal wire is heated to incandescence, electrons evaporate from the metal, or there is what is technically called a thermionic emission of electrons. The pioneer scientists who searched for the laws gov-

erning this emission—its dependence on temperature, for example—were not concerned with any possible practical applications. They simply wanted to understand the process. And yet a direct outcome of their work was the hot filament x-ray tube, and the radio valve found in every wireless set. The same story can be told about those scientists who first investigated photoelectricity, or the emission of electrons when light falls on metals. Today, as a result of their pioneer researches, we have the numerous applications of the photoelectric cell. Dr. K. T. Compton has recently made the statement that industries dealing in electronic devices represent an annual volume of business amounting in the United States alone to $50,000,000.

Again, when Maxwell was investigating the mathematical laws governing the propagation of an electromagnetic disturbance, he little dreamed that his work would lead to radio communication the world over. These are but a few examples to emphasize the fact that the apparent absence of any practical value in scientific research by no means indicates that there will be none. Shrewd business men, men whose ultimate aim is profits, are convinced of the truth of this. In some of the large research laboratories supported by industrial corporations, many investigators are

given a free hand, and are encouraged to get at the bottom of anything they are investigating, whether patents result or not. The corporation directors realize than sooner or later basic discoveries will be made which in the long run may mean increased dividends.

In atomic artillery, therefore, the workers are not thinking about practical results. They are engaged in the fascinating pursuit of knowledge. But even in this field, it looks as if practical results are forthcoming. It seems certain that radioactive substances like radio-sodium can be manufactured in amounts suitable for use in medical problems. Neutrons, too, have alreay been used in biological investigations with possibilities which no man can foresee.

Inevitably those who seek practical results think of the conversion of matter into energy, a question to which we have more than once made reference. Shall we ever be able to control this transformation and harness the released energy? As we stated on page 59, the possibilities are astounding, nay, even frightening. The annihilation of a very small amount of matter would release energy which, if misdirected, could destroy a whole nation. With a civilization which has not yet learned to settle national disputes without resort to fighting, it is to be hoped that the time is far distant when this method of obtaining en-

ergy in unlimited amounts is available. On this score, however, the author of this book is not unduly alarmed. He has great faith in the far-reaching application of the law of conservation of energy. It seems to him to be a foundation stone of the universe in more ways than one. In the last analysis, we do not get something for nothing either in science or in life. Nature provides free of charge vast supplies of water-power, but man must harness this by the sweat of his brow. Man will not harness the energy released by the possible annihilation of matter without expending an equivalent amount of effort. Value given for value received is a basic principle in science as in life.

TABLE III

ATOMIC NUMBERS, ATOMIC WEIGHTS, AND STABLE ISOTOPES OF SOME REPRESENTATIVE ELEMENTS.

Element	Symbol	Atomic Number	Atomic Weight	Mass Number of Isotopes
Hydrogen	H^1	1	1.0081	1, 2, 3.
Heavy Hydrogen (Deuterium) ..	H^2 or D	1	2.0147	
Helium	He	2	4.0040	4
Lithium	Li	3	6.94	6, 7.
Beryllium	Be	4	9.02	9
Boron	B	5	10.82	10, 11.
Carbon	C	6	12.00	12, 13.
Nitrogen	N	7	14.01	14, 15.
Oxygen	O	8	16.00	16, 17, 18.
Fluorine	F	9	19.00	19
Neon	Ne	10	20.18	20, 21, 22.
Sodium	Na	11	23.00	23
Magnesium	Mg	12	24.32	24, 25, 26.
Aluminum	Al	13	26.97	27
Silicon	Si	14	28.06	28, 29, 30.
Phosphorus	P	15	31.02	31
Sulphur	S	16	32.06	32, 33, 34.
Chlorine	Cl	17	35.46	35, 37
Argon	A	18	39.94	36, 38, 40.
Potassium	K	19	39.10	39, 40, 41.
Calcium	Ca	20	40.08	40, 42, 43, 44.
Iron	Fe	26	55.84	54, 56, 57.
Copper	Cu	29	63.57	63, 65.
Zinc	Zn	30	65.38	64, 66, 67, 68, 70.
Silver	Ag	47	107.88	107, 109
Tin	Sn	50	118.70	112, 114, 115, 116, 117, 118, 119, 120, 122, 124.
Platinum	Pt	78	195.23	192, 194, 195, 196, 198.
Gold	Au	79	197.2	197
Mercury	Hg	80	200.61	196, 198, 199, 200, 201, 202, 204.
Lead	Pb	82	207.22	204, 206, 207, 208.

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